2014 — Systems Analysis
Summary of Annual Merit Review of the Systems Analysis Sub-Program

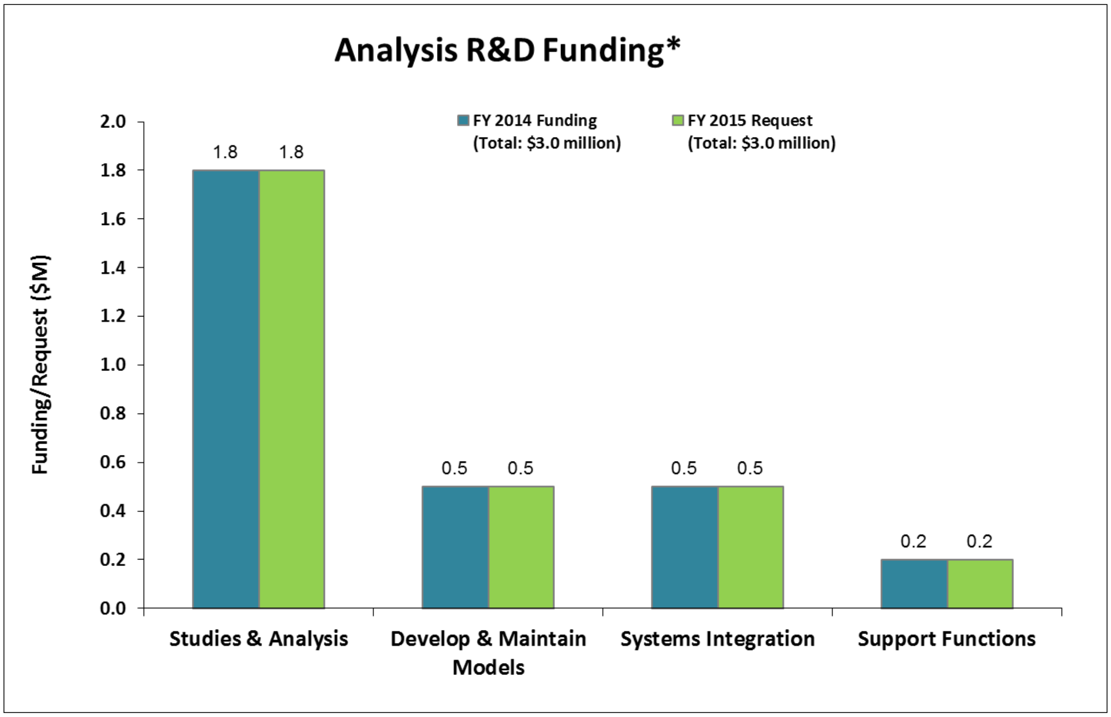
Summary of Reviewer Comments on the Systems Analysis Sub-Program:

The reviewers considered the Systems Analysis sub-program to be an essential component of the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program's (the Program's) mission. The projects were considered to be appropriately diverse and focused on addressing technical barriers and meeting targets. In general, the reviewers noted that the Systems Analysis sub-program is well managed, demonstrates the ability to address immediate analytical needs and overall objectives and plans, and is specifically focused on supporting hydrogen infrastructure development.

Some reviewers commented that the sub-program is effective in providing analytical support and key insights for the Program's research and development (R&D) efforts, and that it is helpful in appropriately directing R&D efforts to address key barriers. Reviewers also commented that the analysis and model portfolio is balanced and making good progress toward understanding the issues, challenges, and opportunities related to achieving the sub-program's technical targets. Some reviewers commented that the models, tools, and financial analyses are helpful in understanding the current status of the technologies and near-term challenges; in particular, they pointed out that the investor workshop is creating awareness among the investment community. Reviewers noted that the Systems Analysis sub-program's collaboration with industry, national laboratories, and academia is strong and provides valuable information and feedback.

Systems Analysis Funding:

The fiscal year (FY) 2014 appropriation for the Systems Analysis sub-program was $3 million. Funding for the sub-program continues to focus on conducting analysis using the models developed by the sub-program. In particular, analysis projects are concentrated on infrastructure development for early market fuel cell introduction, the use of hydrogen and fuel cells for energy storage, life cycle analysis of water use for hydrogen production, employment impacts of developing infrastructure to supply hydrogen for fuel cells, and the petroleum and greenhouse gas (GHG) emission reduction benefits of seven future pathways. The FY 2015 request level of $3 million, subject to congressional appropriation, provides greater emphasis on analysis of hydrogen for energy storage and transmission, early market adoption of fuel cells, continued life cycle analysis of water use for advanced hydrogen production technology pathways, levelized cost of hydrogen from emerging hydrogen production pathways, impacts of consumer behavior, cost of onboard hydrogen storage options and associated GHG emissions and petroleum use, and hydrogen fueling station business assessment.



* Subject to appropriations, project go/no-go decisions, and competitive selections. Exact amounts will be determined based on research and development progress in each area.

Majority of Reviewer Comments and Recommendations:

The maximum, minimum, and average scores for the Systems Analysis projects were 3.6, 3.0, and 3.3, respectively.

Infrastructure: The three analysis projects reviewed in this topic area received a favorable average score of 3.3 for assessing the costs of hydrogen infrastructure development and understanding the hydrogen infrastructure costs compared to other alternative vehicle infrastructure. Reviewers acknowledged that the projects enable a better understanding of station configuration, hydrogen station components, the trade-off between consumer refueling time and vehicle range, and the cost of dispensed hydrogen at various dispensing pressures. The suggested next steps include more in-depth collaboration and consultation with hydrogen component supply companies to calibrate the projected component costs, and reviewers recommended that additional consideration should be focused on the cost of precooling and the cost of compression during station operation.

Model Development and Systems Integration: Two projects involving model development were reviewed (one for assessing the employment and economic impacts of deploying fuel cells and hydrogen infrastructure, and one for life cycle analysis of water use for hydrogen production), receiving an average score of 3.4. These projects received favorable reviews and were regarded as well aligned with the current sub-program goals and objectives.

Reviewers commented that the JOBS and economic impacts of Fuel Cells (JOBS FC) model provides valuable economic and job creation information for project funding justification, as well as informs policy makers regarding regional and national benefits of the technology. Reviewers recommended that the project be expanded to include a comparative analysis with other conventional and alternative fuels and fueling infrastructure, and to include information on the “net impact” of potential job displacement.

For the project *Life Cycle Analysis of Water Consumption for Hydrogen Production Pathways*, reviewers acknowledged that expanding the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model platform to include water use life cycle assessment addresses critical and relevant sub-program issues associated with hydrogen production, and that the comparative evaluation to conventional fuels is significant. Reviewers pointed out that the updated model would be important to policy and decision makers as competition for water resources and energy management increases. Reviewers commented that the future work for the project is robust, but that the project team should ensure the project uses standard methods and protocols with respect to existing water use work.

Programmatic Benefits Analysis: The analysis project reviewed in this topic area received an average score of 3.1 for assessing the costs and GHG emissions for multiple hydrogen production pathways. The reviewers commented that the analysis project to assess the Program's benefits (in terms of cost and reducing GHG emissions and petroleum use) for multiple *future* hydrogen pathways was relevant to the Analysis sub-program's objectives and illustrates the merits of hydrogen as an alternative transportation fuel for light-duty vehicles. Reviewers commented that the future work for the project should include updating the assumptions to a common analysis time period, adding transition analysis to the pathway group, clearly defining the difference between the current analysis and past/future studies on this subject, and examining sensitivity cases relative to decarbonization of the transportation fleet.

Studies and Analysis: Three analysis projects were reviewed and received an average score of 3.3. The projects covered a range of topics, including energy storage, fuel cell cost analysis, and the application of tri-generation fuel cells for infrastructure development in the Northeast. In general, the reviewers felt that the projects supported sub-program goals, but they also agreed that the results of the analysis projects need to (1) include cost and economic evaluations for the tri-generation systems, (2) expand the breadth of the technologies examined for energy storage, and (3) incorporate involvement from additional stakeholders.

For the *Impact of Fuel Cell System Peak Efficiency on Fuel Consumption and Cost* project, the reviewers commented that the project was well executed and useful for generating fuel cell efficiency projections compared to competing vehicle technologies, the impact of fuel cell improvements on cost, trade-offs between fuel cell cost and efficiency, and hydrogen storage costs. The reviewers suggested that the project should compare the fuel cell efficiency to other hybrid and alternative technologies and include additional collaboration with industry stakeholders to improve cost and performance information.

For the *Tri-Generation Fuel Cell Technologies for Location-Specific Applications* project, the reviewers commented that the project is well designed. They suggested that the project be expanded to include other sources of fuel, such as natural gas from a pipeline, and that the economics of the tri-generation system be included in the scope.

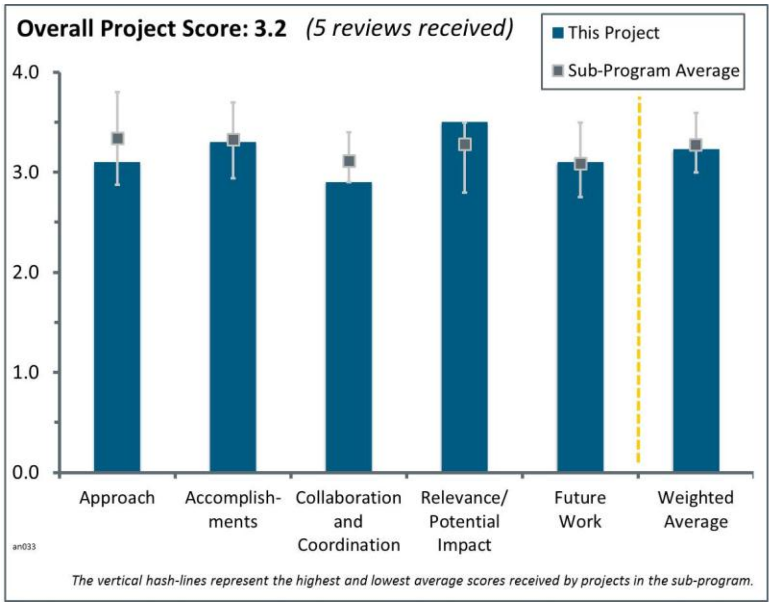
The reviewers of the *Electricity Market Valuation for Hydrogen Technologies* project commented that the study was exceptionally conducted and that introducing hydrogen production technologies to the electrical market is an interesting option to generate a revenue stream. They noted that the project should consider exploring the feasibility of the concept, how these technologies compare against the incumbent technologies that compete in this market, and the market size for this application.

Project # AN-033: Analysis of Optimal Onboard Storage Pressure for Hydrogen Fuel Cell Vehicles

Zhenhong Lin; Oak Ridge National Laboratory

Brief Summary of Project:

The overall objectives of this project are to: (1) develop a method to optimize onboard hydrogen pressure in fuel cell electric vehicles (FCEVs) by integrating a wide range of factors, (2) conduct case studies and provide useful insights for the industry and research and development planning, and (3) identify the optimal pressure that reduces system cost and increases market acceptance of hydrogen FCEVs.



Question 1: Approach to performing the work

This project was rated **3.1** for its approach.

- The integration of Oak Ridge National Laboratory's system analysis tools with other national laboratories' well-established models provides an excellent approach to the main objectives of this project.
- The approach is excellent; however, it focuses on optimization only. In reality, single objective optimization is not the right approach. The project needs to do multi-objective optimization, considering the importance of different vehicle parameters with individual weights—for example, range, cost, fuel efficiency, and infrastructure availability. Such relative optimization gains can be obtained via vehicle choice models. The ultimate goal is to get fast acceptance of vehicles by the market, and cost alone is not the driver. People buy cars for performance, cost, cargo capacity, etc. Changing the pressure of the tanks will affect all of those parameters. The direction of improvement may thus be actually in the opposite direction of the analysis' findings.
- The approach of considering the marginal cost of hydrogen dispensed at various pressures compared to the consumer value of refueling time is a reasonable method of considering optimal hydrogen storage pressure. The proposed value equation and parameters of interest can be used to understand consumer value of various hydrogen pressures. The presentation did not provide sufficient understanding of how key parameters (i.e., hydrogen station cost, consumer value of time, and refueling annoyance factor) were derived or whether these values were validated or peer reviewed. The presentation provided too little information on the details of the approach and where the values and parameters used in the analysis came from. This makes an assessment of the validity of the findings difficult. There are insufficient details provided about the hydrogen optimal pressure model and how it has been validated and/or peer reviewed. A baseline consumer value of time of $100/hour coupled with a refueling annoyance factor of 3.5x—yielding an overall consumer cost of refueling time of $350/hour—seems very excessive. It is unclear whether a value of $350/hour of consumer time has been validated against existing literature.
- Given all the parameters that could be optimized in the model, it is a good idea to build a user interface to allow the user to choose the appropriate inputs for different scenarios instead of trying to optimize everything at the same time. It is difficult to understand why onboard storage cost increases as a function of pressure. Vehicle manufacturers are set on a 10,000 psi storage tank. Therefore, the cost/size of the tank will be the same regardless of the pressure at which it is refilled. It is not clear why the marginal station cost line is always flat. At 700 bar, there should be a much higher cost given the additional compression and cooling required to meet the 3 minute fill-up time requirement. It is also unclear whether what is being proposed is a station that only refuels at one particular pressure or a station with the flexibility to dispense hydrogen at different pressures/costs. It would be good if the model could optimize pressure from the point

of view of the station owner and not only from the consumer's point of view. From the slides alone, it is unclear how the refueling inconvenience cost is calculated.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- The project provides a useful analysis of clustered deployment strategies versus region-wide infrastructure deployment. The project has developed appropriate analyses of optimal hydrogen dispensing pressure considering different values of consumer time, hydrogen station deployment strategies, and driving intensity. The findings of the project would be strengthened through better validation of the underlying assumptions, including the assumptions of consumer value of time, hydrogen cost, and hydrogen station cost. The analysis should consider lower overall values of consumer time. It appears that the lowest value of consumer time (including a baseline time value of $50/hour and annoyance factor of 3.5x) is $175/hour. Though it may be useful to consider an annoyance factor, lower overall consumer time values should be investigated.
- This project has made significant progress to include the development of a friendly user-interface, the analysis of optimum pressure under cases reflecting zero-emission vehicle (ZEV) scenarios, and the sensitivity analysis. It is very interesting to see that the new results suggest that 700 bar may not be the optimum pressure in ZEV scenarios under a cluster strategy.
- The principal investigators (PIs) have accomplished the majority of the work. They seem to be on schedule. It is not logical that the marginal station cost curve is flat—the (PIs) should review compression and cooling assumptions for high-pressure dispensing. The incremental cost curve should not be flat, but instead show a step increment when additional cooling and compression is needed to refuel at the appropriate pressure in under 3 minutes.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- More collaboration with car original equipment manufacturers (OEMs) or vehicle choice modelers would be necessary for adequate analysis.
- The project notes useful collaborations with other industry, academic, and national laboratory researchers. Greater collaboration with Argonne National Laboratory (ANL), including the incorporation of its latest findings on hydrogen station costs, particularly station costs for various dispensing pressures, would strengthen the analysis.
- There is good collaboration with other national laboratories and industry. Researchers will benefit if they consider additional collaboration work with automotive OEMs.
- The U.S. DRIVE Fuel Pathways Integration Technical Team (FPITT) has not had a chance to comment on the latest version of the model. It is suggested that a beta version of the model be shared with potential users before public release. Although there seems to be collaboration with Hydrogen Analysis model (H2A) developers and the National Renewable Energy Laboratory, there seems to be some disconnect. The vehicle miles traveled used in these analyses were "1.3 k mile/y" (presumably 13,000 mi), while H2A and the Macro-System Model use 15,000 miles/year. Also, it is unclear if this project would benefit from incorporating the work that ANL is doing on station cost at different fueling pressures to optimize precooling.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- The project enables a better understanding of the trade-off between consumer refueling time and the cost of dispensed hydrogen at various dispensing pressures. The project provides a more thorough understanding of the cost of dispensing hydrogen at various pressures, which may aid DOE in understanding how to develop an adequate network of hydrogen refueling stations given a fixed amount of investment capital available, particularly in the initial rollout years for infrastructure deployment.
- This is a very important analysis, although ultimately DOE has limited leverage on its acceptance by OEMs. The OEMs have full expertise of what trade-offs to make for successful vehicle sales.
- Understanding the relationships between hydrogen pressure and range, costs, and consumer acceptance is key for the early development of the hydrogen market.
- It seems that the whole industry moved to 10,000 psi to achieve a range comparable to internal combustion engine vehicles without consideration of other factors such as cost to consumer or station cost. It is good to see an analysis of the trade-offs among different refueling pressures. Even if automakers continue to target 10,000 psi, that does not mean that the consumer cannot refuel at lower (cheaper) pressures.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work will add great value to achieving the main objectives of this project.
- The presenter notes a wide range of future activities that would aid in DOE’s understanding of optimal hydrogen dispensing pressure. The proposed future work appears quite extensive, especially considering the time and budget remaining in the project. It would be useful to better understand the actual expected future work versus potential future work if additional funding is provided. Future work should consider better validation of underlying assumptions and modeling and peer review of the analysis, which would strengthen the findings. Future work should consider a wider range of consumer values of time, particularly lower values of time. Future analyses should consider refueling annoyance factor as a sensitivity analysis while maintaining an analysis that does not incorporate an annoyance factor.
- The proposed future work seems good. Seeking comments from the FPITT on the user interface is recommended. It would also be good to see an option in the model for the station owner to minimize cost. Also, the project could integrate ANL’s modeling efforts on optimal cooling for different refueling pressures.
- It seems like the major questions have been answered, and the project does not warrant another year of funding.

Project strengths:

- The project’s understanding of the subject is a strength, as are the modeling capabilities and user interface.

Project weaknesses:

- Perhaps this is not a weakness, but it seems that the cluster strategy is unrealistic; getting a relatively large number of people who live within a few miles from each other to all buy FCEVs at the same time seems unrealistic. The project could use more interactions with other hydrogen modelers to check assumptions.
- It is not clear if this will actually be implemented by stations. H2USA has a cost/utilization model that will likely be more widely adopted than this tool. Consideration should be given as to how this can complement H2USA activities. Otherwise, this is duplicative and competitive with H2USA.

Recommendations for additions/deletions to project scope:

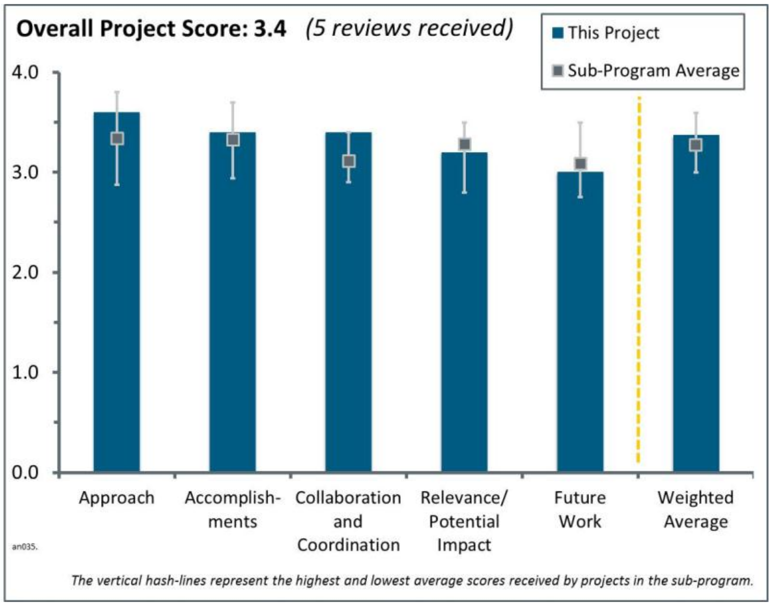
- This project appears complete.
- The researchers should incorporate contributions from modelers such as those working on the Automotive Deployment Options Projection Tool (ADOPT) and the Market Acceptance of Advanced Automotive Technologies model (MA3T). Also, they should incorporate reviewers from automotive OEMs.
- The project team should conduct analysis from the point of view of station owners and better define what elements are considered in the "station cost" analysis. It is unclear whether additional cooling and compression are considered for stations dispensing at higher pressures. Given that the marginal station cost is flat, it seems that the additional costs of precooling and compression have not been considered. The team should check its assumptions with ANL and describe how the refueling inconvenience cost is calculated.

Project # AN-035: Employment Impacts of Infrastructure Development for Hydrogen and Fuel Cell Technologies

Marianne Mintz; Argonne National Laboratory

Brief Summary of Project:

The objectives of this project are to analyze the economic impact of hydrogen and fuel cell deployment, to provide input for evaluating research and development and deployment targets, to develop a consistent framework for evaluating economic impacts of hydrogen infrastructure deployment, to compare alternative hydrogen station rollout scenarios, to develop robust and user-friendly tools with appropriate functionality, and to provide web-based training and support to enable economic impact analyses of hydrogen infrastructure deployment.



Question 1: Approach to performing the work

This project was rated **3.6** for its approach.

- Identification of the economic impact and job creation for alternative fueled vehicles and alternative fueling will be a critical policy consideration. The project work is user-friendly and will be accessible, standardized with a spreadsheet-based framework, and relevant with outputs providing economic impact and job creation information.
- This is fantastic work!
- The approach seemed straightforward, and the project seems in line with the objectives. However, it is unclear how partial jobs were dealt with. Some activities are responsible for only a part of a job. The speaker mentioned that jobs create indirect jobs and the effect ripples through the economy. It is not clear when to stop counting.
- This is a good model for analysis, but it is not clear who the target audience is.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- The project is ready for launch.
- The project is making good progress on the stated goals of determining the number of jobs and in what sectors they occur. At least, these are the goals that the reviewer assumes the project is trying to achieve.
- There is very good progress with the development of the spreadsheet, default input fields, and model calculations. Additional work to conduct a peer review with additional industry developers to confirm input defaults and output calculations would be of value.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.4** for its collaboration and coordination.

- Collaboration with institutions was excellent, but additional work will be needed to complete a peer review with industry developers to confirm input defaults and output calculations.
- There is good collaboration with other institutions.
- The project team has made a thorough effort to solicit feedback from stakeholders.
- More collaboration from policy analysis experts—for example, professional economist organizations—would have been expected. While inputs are great from stakeholders, economic analysis and jobs impact are a relatively new analysis pathway, and wheels might be reinvented unnecessarily.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- An understanding of the economic impact and job creation for alternative fueled vehicles and alternative fueling will be a critical policy consideration and is important for decision making. The approach is well supported and will be of high value. The project tool is user-friendly and will be accessible, standardized with a spreadsheet-based framework, and relevant with outputs providing economic impact and job creation information.
- This is a key area of research, which would inform policymakers regarding regional and national benefits of the technology.
- This could be used by certain policymakers to justify funding hydrogen infrastructure; however, the number of jobs estimated by this model is very low. There should be some analysis on how much money is spent in order to create one job.
- Perhaps job creation will happen in any alternative fuel sector. For example, electric vehicles will give a big boost to electricians, and they will spend their money at Starbucks. It is not clear whether the goal is to rank which alternative fuel will give the most benefit to the economy as a job creator. If electricity requires fewer jobs to be created, it is not clear whether this is better or worse. It is not clear whether this project is just quantifying effects or making value judgments. This has the potential to be very useful in quantifying numbers for reports and showing lawmakers the potential impact that hydrogen has on the economy.
- It is not apparent how effective this tool will be and who it is targeted to. The researchers need to convince fueling companies, station owners, etc. to construct new stations and install hydrogen dispensers at existing ones—it is not clear whether job creation is the driving force for this. The project needs to show payback, economic impact, and other data that would encourage station development.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- While the work is of high value, relevant, and well executed, additional work will be needed for review by developers. In addition, there should be consideration to expand the project to include a comparative analysis with other conventional and alternative fuels and refueling technology, and to include information on potential displacement of jobs to identify net changes.
- The project should take feedback from stakeholders to plan future work. There are still many variables and areas to add/investigate to make the tool more effective.
- The proposed future work does not seem to justify the proposed budget of $200,000. The planned activities seem to require less effort than those in the past year, which had a smaller budget.

Project strengths:

- The strengths include the following: relevance for policy and decision making, development of a tool that is user-friendly and will be accessible, and development of a tool that provides consistent and standardized results tailored to specific regions for accurate project assessments.
- The strength of this project is that it is straightforward, and the project is accomplishing its goals in a systematic fashion. This creates the political imperative to continue hydrogen work.
- Any model or analysis tool is needed, as the industry is finding footholds and proving itself to be a worthwhile technology to pursue.

Project weaknesses:

- Beyond creating good numbers for policymakers, it is not clear what the broader impact is. These jobs are created whether or not the project is completed.
- The weaknesses include the following: need for additional technical and economic peer review by hydrogen station developers, need for development of a comparative analysis with conventional and alternative fuels and refueling, and need to include displaced jobs for net results.
- The number of jobs created is low. Therefore, this could have a negative impact on hydrogen infrastructure given the amount of investment.

Recommendations for additions/deletions to project scope:

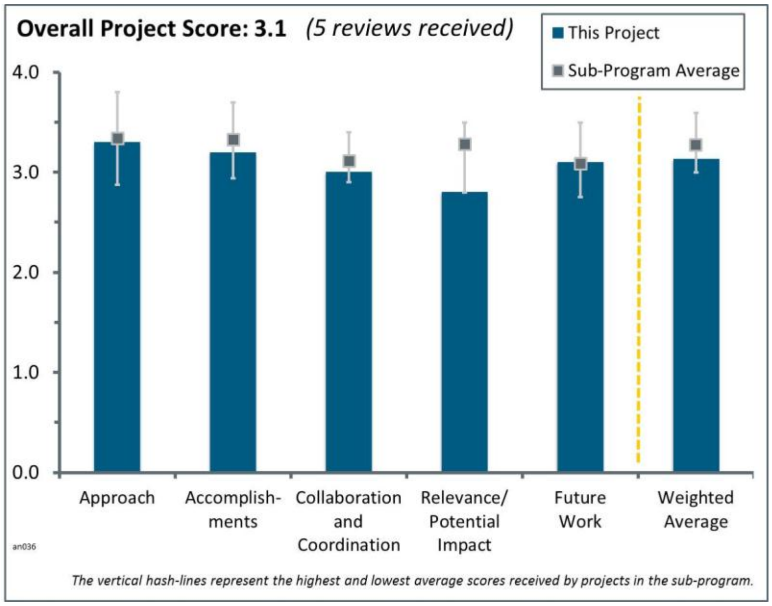
- The team needs to market this tool to the right audiences. The analysis should include adding a single pump at existing stations, as that is a direction some companies are taking in California.
- The project should reintroduce displaced jobs (even if in a cursory manner). Also, if at all possible, an indication should be added as to the skill levels required by the work for possible extrapolation to the associated salaries.
- The fiscal year 2014 budget should be lower. The project seems close to completion without much extra effort required, unless progress has been overstated in these slides.
- The project should do the following: provide resources for additional technical and economic peer review by hydrogen station developers; expand the scope for development of a comparative analysis with conventional and alternative fuels and refueling; consider expanding the scope to include displaced jobs for net results; consider where the spreadsheet tool will be located and promoted to provide effective public use by policymakers for objective decision making—placing the spreadsheet in a comprehensive alternative fuel transportation site/location would be advantageous over placement of the tool in a hydrogen silo site/location where it may be overlooked.

Project # AN-036: Pathway Analysis: Projected Cost, Life Cycle Energy Use, and Emissions of Future Hydrogen Technologies

Todd Ramsden; National Renewable Energy Laboratory

Brief Summary of Project:

The objective of this project is to conduct cost and life cycle energy and emissions analyses of complete hydrogen production, delivery, and dispensing pathways using the Macro-System Model (MSM) to evaluate hydrogen cost, energy requirements, and greenhouse gas (GHG) emissions. The project provides detailed reporting of assumptions and data used to analyze hydrogen technologies, enabling consistent and transparent understanding of results, and obtains industry review of the input parameters and the models used.



Question 1: Approach to performing the work

This project was rated **3.3** for its approach.

- The project utilizes a highly structured approach to perform life cycle analyses of energy and emission costs associated with different hydrogen production and delivery scenarios. The approach appears to be similar to other projects (e.g., AN-044) supported by the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program and, as such, has a common basis for comparison with other analyses.
- The analysis is very rigorous, detailed, and well documented. It addresses the important objective of understanding the costs and impacts of advanced technology in a mature market. We need to know more, but we need to know this. Appropriate modeling tools and data were used. The key barriers have to do with the transition. It is understood that transitional analysis is not within the scope of this study, however.
- Analysis tools supporting the project are well developed and integrated in the overall analysis.
- The project uses the MSM to analyze hydrogen production pathways; it therefore uses a number of key models to provide valuable analysis of hydrogen production. It is not clear, though, how DOE is using this modeling data to identify critical areas for future research highlighted by the models as critical bottlenecks. The assumptions seem reasonable, but it is hoped that as fuel cells and stations roll out, these can be changed to match the situation on the ground.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.2** for its accomplishments and progress.

- Excellent progress has been made. The current technology analysis is complete and published. Most of the pathways of interest have been completed, and results were presented.
- The life cycle analysis for various hydrogen supply pathways is imperative to DOE's overall efforts towards understanding the environmental and cost impacts of future energy supply options. Objective analysis is instrumental for DOE, industry, and other stakeholders in defending the merits of hydrogen energy in comparison to other energy vectors.
- The group has published a comprehensive report, and a large amount of good work has been performed. Where bottlenecks in costs are identified, DOE should consider directing research to address these.
- The accomplishments and progress are consistent with the level of support.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- Collaboration with other institutes is excellent—the project incorporates models and tools developed not only at the National Renewable Energy Laboratory but also Argonne National Laboratory and Sandia National Laboratories. The project works closely with Alliance Technical Services and the U.S. DRIVE Partnership to coordinate input used in their studies.
- In building on many years of previous work, broad collaboration is not necessarily required. The collaboration for this project is aligned to the project size and scope. The analysis is indirectly supported with the maintenance and continuing development of multiple models and tools from others areas of DOE, and this should be noted.
- For this study, it is not so much a question of collaborating with others but of making appropriate use of the models and data developed by others, and this was done.
- The project is reviewed by industry through the technical team, but the principal investigator should consider closer interactions with similar efforts worldwide to give the validation additional strength.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **2.8** for its relevance/potential impact.

- Project analysis clearly shows the merits of hydrogen as an alternative transportation fuel for light-duty vehicles and that hydrogen can be supplied through a number of hydrogen supply pathways. From an industry perspective, the analysis does highlight some concern on what are viewed as “stretch targets” contained in the analysis in the area of polymer electrolyte membrane water electrolysis efficiency.
- It is critical that DOE use up-to-date data to do a thorough analysis of all hydrogen production pathways, provide feedback to the technical task, and update these analyses with real-world learning as new technology comes online and the hydrogen economy rolls out.
- With fuel cell electric vehicles (FCEVs) still in their infancy, the hydrogen fuel costs are highly speculative. A comparison of the “Total Cost per Mile” pie chart (slide 12) with the chart shown in the 2013 review shows significant differences, and thus one wonders how sensitive the results are to input—especially with respect to how accurate the input is and how much it varies from year to year. As good as the approach is, it is of limited use if the input data are not known with sufficient accuracy. The GHG versus fuel cost information on slide 20 shows different data from those contained in the 2013 review—especially for the 2020 baseline gasoline vehicle and the 2020 electric gas hybrid. The reason for the differences is not clear.
- Premises are critically important. The standard premise for a study should be that the context is a concerted effort to reduce GHG emissions across the economy. It is a step in the right direction (but not enough) to run a green grid case (or cases). The basic premise should be that hydrogen is being introduced in an economy that has taken meaningful steps (in the long run since this is a mature market analysis) to reduce GHGs. This would affect not only the grid but all aspects of industry and transportation. Admittedly, this is difficult to do. It would require estimating how much biofuel is being used and what its well-to-wheel emissions are. It would also require assessing how energy efficient the vehicles, buildings, etc. are. Yet if a fundamental goal of hydrogen is to reduce GHG emissions, for a long-run lifecycle analysis, its impacts should be placed in the context of a world in which GHG mitigation has been achieved throughout the economy. This should be the default assumption, and sensitivity cases should be run relative to the default.
- The relevance of this project is not certain. This analysis appears to have been done many times before. It is unclear what the value added is.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The future analysis does not contain the evaluation of current hydrogen supply pathways that are expected to provide favorable life cycle emissions and low cost. This includes the evaluation of biomethane as a renewable energy feedstock for hydrogen using steam methane central and distributed reforming pathways. Furthermore, the central hydrogen pathways for steam methane reforming (SMR) should include the tri-generation of hydrogen, steam, and power.
- The future activities are a logical progression from the work performed thus far.
- Given the scope of the study, the proposed future work is very appropriate and will be useful. However, there are concerns related to the premises of the study.
- The project will also look at future hydrogen pathways and provide a very useful ability to compare to current hydrogen pathways.

Project strengths:

- Using MSM to provide critical data to DOE and stakeholders is a strength.
- The project foundation is based on well-developed and industry-accepted models and tools.
- The project's rigor, appropriate use of models and data, and careful documentation are strengths.
- The project has a consistent approach in analysis across the board—allowing for an accurate comparison of different pathways.

Project weaknesses:

- The project may not be nimble enough to react to rapidly changing energy scenarios.
- Key input parameters and modeling assumptions underpinning the analysis should be updated for consistency and the latest information that reflects current market progress. Overall, there is a need to refresh the analysis assumptions to a common analysis time period (i.e., the project currently has a 2025 start-up year, but results are reported in 2007 dollars and based on 2009 energy costs) and assumptions (40-year analysis for central production versus 20-year analysis period for distributed production).
- The approach, while being consistent, is being used to analyze FCEVs that are insufficiently mature to yield accurate input data for comparison of the different pathways.
- The project needs to move into transition analysis and needs to reconsider premises concerning GHG mitigation throughout the economy.

Recommendations for additions/deletions to project scope:

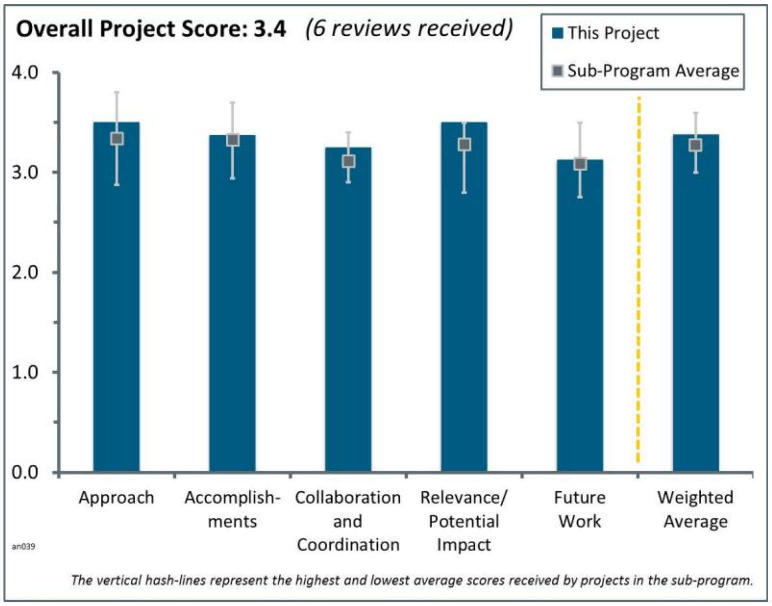
- The project should continue to evaluate current and future hydrogen production pathways.
- The analysis should incorporate more immediate supply pathways, such as SMR of biomethane along with tri-generation of hydrogen, steam, and power for central steam methane reforming. Based on the set of assumptions, the project may want to make hydrogen stakeholders better aware of what the $2–$4/kg cost target really means in current and future dollars.
- The project requires better input information on costs and emissions for the different pathways being considered—perhaps the project should focus on developing high-fidelity data rather than expanding the project to consider different pathways.
- The project should add transition analysis, establish the decarbonization of the U.S. economy as the default assumption, and run sensitivity cases relative to that.
- Many aspects of this project appear to have been done in previous studies. These hydrogen pathways seem already to be well characterized by existing analyses and modeling tools developed by the national laboratories.

Project # AN-039: Life Cycle Analysis of Water Consumption for Hydrogen Production Pathways

Amgad Elgowainy; Argonne National Laboratory

Brief Summary of Project:

The overall objective of this project is to develop water consumption as a new sustainability metric for evaluating the production of energy products. Life cycle analysis (LCA) is needed to estimate water consumption to provide a consistent accounting of water consumption of transportation fuels (including hydrogen). Argonne National Laboratory is expanding the Greenhouse Gas, Regulated Emissions, and Energy Use in Transportation (GREET) model to assess life cycle water consumption along the pathways of producing transportation fuels from various feedstock sources.



Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- The approach is good. The fact that water LCA will be integrated into GREET so that the model will become more comprehensive (and more complex too, unfortunately) is appreciated. This model could benefit from being more specific about the sources of fresh water—water consumption in areas where water is abundant is not as big a problem as consumption in places like California, where there is a persistent drought.
- This is a good strategy for water in the hydrogen cycle. It is a good strategy to compare with gasoline vehicles. It is a very ambitious approach. The project needs to show why and how water plays a role in hydrogen production.
- It is an excellent approach to use comparative analysis for identification of water use by fuel production and by per mile pathways. The approach is sound, but development of the data and review for various fuels and pathways will be challenging.
- The project addresses a critical need by adding water consumption to the GREET model for all fuels and is thus addressing many of the analysis barriers.
- The work has been carried out in an organized and effective manner.
- Generally, the approach to incorporating water analysis into GREET is good. It would be good to see more of the thoughts on how to combine water availability and water use to capture the regional nature of the water issue.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.3** for its accomplishments and progress.

- There is very good progress given the complexity of finding the appropriate data sources to integrate into GREET. The principal investigators (PIs) claim to have completed 70% of the original goal. The reviewer would agree and proposes that the project be extended to include GREET2.
- The work done so far is impressive. It is clear that progress has been made, and there are no faults here.

- Evaluation of the water footprint for the major fuels is a significant result. Quantification of water treatment impacts has a significant impact. The pathway comparison is a valuable development.
- Inclusion of steam methane reforming (SMR) and water electrolysis and conventional fuels is an accomplishment that will be very useful in the future as the United States moves to an independent, sustainable energy economy. The conclusion that most of the water in fuel production is used for irrigation for farming, used for cooling in thermoelectric power generation, and lost in evaporation in hydroelectric power generation is somewhat obvious. What is needed now is a metric by which we understand what water is really lost from the system. In all of the above cases, most of that water is returned to the supply; assuming water used for hydroelectric power is consumed in the western United States, it presumably falls as rain further east, and the irrigation water and cooling water are returned to rivers and streams, which allows the water to be re-extracted, treated, and re-used. Water for fracking is definitely lost, as it is injected into a deep aquifer now, but may be recycled in the near future. Water for hydrogen production is presumably lost at the point of manufacture but is returned as water at the point of consumption. This complicated picture needs a better representation in the model output.
- The comparison of LCA water impact is very nice. The tri-generation system does not need external water for hydrogen during steady state operation.
- Progress and accomplishments are in the initial stages for development, and additional work may be needed to collect additional data on fuels and pathways, to confirm data and assess accuracy, and to display results confidently as a comparative analysis that can be used to support policy for water conservation with energy management. Additional consideration should be made to determine if/how resources in both time and funding are adequate to complete the analysis.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- Researchers involved all the DOE technology offices that are needed to provide input to the model. Furthermore, they reached out to individual organizations and U.S. DRIVE Partnership technical teams for input.
- There is a good mix of collaboration with industrial collaborators and the U.S. Geological Survey. However, with such a complicated resource issue, more collaborators are definitely desirable.
- There has been some collaboration with industry and government. It would be better to see more involvement by industry for each of the pathways that have been chosen. Three real-world data points for two of the pathways (SMR, electrolysis) are a good start, but this needs to be expanded.
- There was reasonable collaboration with industrial users for large SMR and forecourt electrolysis. Water usage from forecourt SMR would be a useful addition.
- Coordination was good, but coordination with others from international markets and collection of data from industrial participants will be needed to resolve significant range discrepancies and confirm accuracy.
- Collaboration was not covered sufficiently to make comments.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.7** for its relevance/potential impact.

- GHG and energy efficiency have lived in an LCA vacuum for a long time. Given all the water issues faced by industry, regulators, and communities, water consumption needs to be integrated as a functional unit when comparing energy sources and vehicle technologies. The 2014 National Climate Assessment states, “Changes in water availability, both episodic and long-lasting, will constrain different forms of energy production... Extreme weather events and water shortages are already interrupting energy supply, and impacts are expected to increase in the future... Producing energy from fossil fuels (coal, oil, and natural gas), nuclear power, biofuels, hydropower, and some solar power systems often requires adequate and sustainable supplies of water. Issues related to water, including availability and restrictions on the temperature of cooling water returned to streams, already pose challenges to production from existing power plants and the ability to obtain permits to build new facilities."

- To make the correct decision for future energy use, we must have water consumption in the models, so the impact here is very high.
- This is a high-value topic that will have increasingly important policy and decision-making implications as competition for water resources and energy management increases.
- Developing an understanding of water is an important component of systems analysis. This project should be further supported to assist in an accurate assessment of the state of hydrogen and electrified vehicles regarding the environmental impacts.
- Incorporation of major pathways is important for the GREET model. Minor pathways are nice for completeness but are not as relevant as the major pathways.
- The relevance is not clear.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The future work proposed will make important additions to the model. The comprehensive detail that the project will provide is appreciated; covering all the bases will make the output far less susceptible to criticism.
- The proposed future work is good. It is a staged approach, which makes sense because some pathways will be useable before the entire project is complete. It would be good to see more attention paid to documenting the sources of the information and assumptions. It would be best if these could be documented in a central location. The planned future work to reconcile the different water consumption concepts is very important, and it would be good to see a bit more definition around that.
- The inclusion of other pathways is important for completeness and to allow comparison of all options. Regional aspects should be addressed at "extremes" first to assess sensitivity to region. Impacts associated with purification are a good addition.
- It is encouraging to see that resource availability will be considered, although it is difficult to fathom how that will be measured within GREET. One of the bullet points under future work includes "develop water factors for vehicle materials." The reviewer is assuming that would feed into GREET2, which the reviewer would really like to see. It would be interesting to compare water consumption for different vehicle technologies. It is not clear how much water is needed to produce an internal combustion engine vehicle versus a battery electric vehicle. The PIs have a very clear understanding of where potential issues/areas of improvement lie and seem to be grappling with integrating a solution to these issues into the water model.
- Water from tri-generation plants should be considered as higher priority. It is a "no-water-needed" case for hydrogen or cooling.
- Comparative analysis for water use for fuel production and pathways will be very important and increasingly relevant, but attention is needed to collect and confirm data.

Project strengths:

- The analysis builds on a robust framework of life cycle analysis. It is structured in a logical manner, and the work is thorough.
- The PIs have the best understanding of how GREET works and are the best suited to incorporate new data into the model.
- The project represents a solid analysis. It builds on a strong background of the Hydrogen Analysis model (H2A), Hydrogen Delivery Scenario Analysis Model (HDSAM), and GREET model.
- The project adds water consumption to the GREET model, thereby strengthening the usage of the model.
- Fuel cells and hydrogen benefits are most important.
- Strengths include relevance, approach for development of a comparative analysis, and scope for production of fuels and use by pathways.

Project weaknesses:

- Definitions of water use are not always clear and meaningful (primarily for hydroelectric generation).
- Documentation of data sources for input assumptions and reviews of this project with stakeholders appear to be somewhat lacking.
- The project will always fall short in its representation of a complex problem, so the range of water consumption should always be included.
- The project is very ambitious, complex, and easy to misunderstand.
- Weaknesses include the tedious work needed to collect additional national and international data on water use, resolve wide ranges of data, confirm gross and net water use, and correct any miscounts or double counts of water use.
- Water issues are regional, and it will be difficult to portray these differences in the current version of GREET given that it does not have a mapping/geographic information systems component. GREET will become even more complex given the integration of a water component.

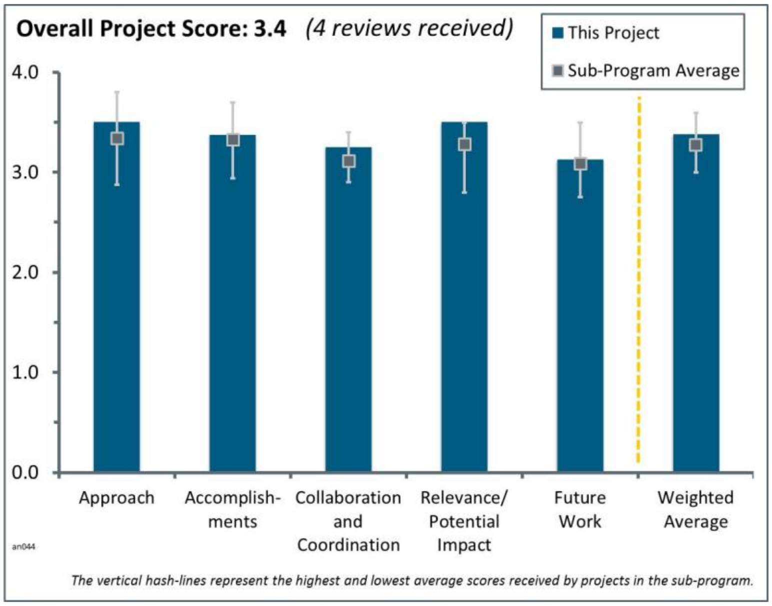
Recommendations for additions/deletions to project scope:

- It would be interesting to see the GHG, energy, criteria air pollutants, and water consumption of different fuels and vehicle technologies represented in one chart. Water consumption should be incorporated into GREET2, and ranges should be included in the results to show the variability of the data.
- This may already be part of the planned future work on reconciling water consumption concepts, but it would be beneficial to see a definition of the water impact that includes the regional availability, as well as the consumption. Alternatively, it would be valuable to incorporate into GREET the function of determining where water use occurs, leaving the impact analysis to others. Basically, defining the regional water use is very important because all water use is not created equal.
- The project should do the following: consider the cost of water treatment from produced water and the severity of pollution of various grades of produced water; include next-generation hydrogen production, such as algal and photoelectrochemical methods; in addition to consumption range, include statistics on how likely a particular level of water consumption is (e.g., evaporation in a dry year versus a wet year, maximum water for corn production, where and when, etc.)
- The project should ensure that work uses standard methods and protocols with respect to existing water-use work to facilitate comparisons with work done outside of DOE.
- The team should include comparison of hydrogen with other fuel options on the LCA basis.
- This is a relevant topic, but additional resources and time will be needed to collect additional national and international data on water use, resolve wide ranges of water-consumption data, confirm gross and net water use, and correct any miscounts or double counts of water use.

Project # AN-044: Impact of Fuel Cell System Peak Efficiency on Fuel Consumption and Cost

Aymeric Rousseau; Argonne National Laboratory

Brief Summary of Project:



The objectives of this project are to evaluate the benefits of aggressive fuel cell system peak efficiency compared to the current target of 60% from an energy consumption and cost point of view, and to evaluate the potential of technologies to accelerate petroleum displacement. Full vehicle simulations were performed to assess the vehicle energy consumption and cost of current and future fuel cell electric vehicles (FCEVs) compared to conventional powertrains as well as aggressive fuel cell system peak efficiencies.

Question 1: Approach to performing the work

This project was rated **3.5** for its approach.

- Use of the Autonomie model, which has been well vetted and is a well-regarded model for advanced vehicle simulations, is an excellent approach to understanding fuel economy improvements from advancements in fuel cell stack efficiency. The analysis of a range of vehicle classes and sizes and comparison to other vehicle types, such as conventional gasoline vehicles and hybrid electric vehicles (HEVs), helps provide a better understanding of how FCEVs perform in relation to competing vehicle technologies.
- There is very good connection with U.S. Department of Energy (DOE) goals. Greater than 60% peak efficiency is a good start to guide component development. Connecting with DOE advanced technology improvement work is a timely strategy. Technical Team feedback is a productive connection. The project makes good use of modeling tools and stakeholders, including the U.S. Environmental Protection Agency (EPA) drive cycle. Assumptions are realistic and hence beneficial.
- The approach is reasonable and uses appropriate data inputs (from Strategic Analysis, Inc. and EPA cycles).
- The project is well designed, but it is difficult to understand the objectives of the work given the description in the presentation. The principal investigator should revise all of the language on slide 3, define each scenario, and describe the DOE barriers that are being tackled. The barrier described in the project is "provide guidance on component targets and future [research and development] directions." That is not a barrier; that is an objective. This project basically compares current fuel cell efficiency (~60%) to a theoretical high efficiency that could be achieved in 2030. Both of these scenarios are then compared against current and future internal combustion engine (ICE) vehicles. It takes a while to understand that because in slide 3, the 60% fuel cell efficiency is referred to as a "goal," when in fact, that is the current efficiency of the fuel cell. It is difficult to understand what an "aggressive" fuel cell system performance means. Slide 26 states that the tank mass shrinks as the efficiency of the fuel cell increases. It is understandable why this analysis is being done, but if the assumption is that the tank size is optimized to reduce cost, this seems unrealistic given that automotive manufacturers are set on a 10,000 psi tank that can provide at least a 300-mile range, although more mileage, and therefore a larger tank, would translate into additional zero emission vehicle credits.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.4** for its accomplishments and progress.

- The analysis provides a very good understanding of the impact of fuel cell stack efficiency improvements on FCEV fuel economy across a range of vehicle sizes and classes. The findings of how fuel cell stack efficiency improvements lead to improvements in vehicle weight associated with the reduction in the need for hydrogen storage and other subsystems are significant and help show how fuel cell stack improvements lead to overall FCEV system improvements. The analysis provides an excellent look at FCEVs (across different classes) compared to conventional vehicles and HEVs.
- The team's use of probability for high targets is a good idea for productive simulation. For weight, the inclusion of multiple vehicle categories is useful for analysis. Multiple improvements with hybrids make a better impact. On-board hydrogen storage of 5.6 kg yields a range of more than 320 miles for all cars in this analysis, which is good news. The 60% to 65% efficiency improvement is very beneficial. Projected benefits justify continued DOE investment to 2030. Cost benefits results are confusing—the balance between capital expenditures and operational costs needs better understanding.
- It seems that the bulk of the work has already been completed. The project contributes to overcoming barriers outlined by DOE and meets the expectations outlined in the scope, but it does not add very much to the body of science. We already knew that higher-efficiency fuel cells would improve the economics of FCEVs and improve miles per gallon.
- It would be useful to have actual fuel efficiency projections. Relative numbers and gains are okay, but fuel efficiency projections can more directly feed into other modeling efforts.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.3** for its collaboration and coordination.

- The project benefited from consultation and collaboration with the U.S. DRIVE Partnership, including vehicle manufacturers. The project lists collaboration with industry and academia, but it is not clear how these actors were engaged or what information they provided. It seems likely that the project benefited from the data, modeling, and assumptions embedded into the Autonomie model, but as development of that model was outside this project, it is unclear how the model utilized industry and academic input on vehicle parameters.
- There are good collaborative efforts. Adding stakeholders such as battery electric vehicle (BEV) manufacturers, such as Tesla, is suggested.
- Collaboration with other government entities and laboratories seems appropriate. However, it is hard to tell whether collaboration with experts has been appropriate because there is no information about who was involved and how many people participated or whether the results of the Autonomie runs have been submitted to the "experts" to vet the validity of the results.
- The project could stand to benefit from direct collaboration with original equipment manufacturers (OEMs) for benchmarking analysis results. It is also unclear if the project findings and tradeoffs are in line with typical OEM behavior. For example, higher efficiency may yield larger cars while keeping tank size the same.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.5** for its relevance/potential impact.

- This is one of the most important parameters of FCEV—as it has an impact on the size of production, distribution, and dispensing requirements per vehicle, as well as revenue per car and emissions footprints.

- The project provides guidance to DOE on FCEV research priorities by helping with understanding of the impact of fuel cell stack improvements on FCEV performance, including a comparison of FCEV performance to conventional and HEV.
- This is very important work to guide future improvements and funding. It will be nice to connect with the driving factors that improve system efficiency.
- This seems to be a good update to the Autonomie model, which is good to do on a regular basis to capture technology changes. The update is particularly important given that other models get input from Autonomie. However, the results contribute very little to the existing body of knowledge.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Comparisons with competition and advanced hybrid concepts will be beneficial.
- The barrier described in the project is “provide guidance on component targets and future [research and development] directions.” That is not a barrier; that is an objective. It is hard to tell whether the proposed future work is focused on critical barriers or will overcome them because no barriers are described. The barrier is the lack of understanding of how fuel cell efficiencies will improve in the future and what components will contribute to a reduction in cost and an improvement in fuel efficiency. With that in mind, the future work described in slide 16 seems appropriate. In particular, it would be nice to see future vehicle technologies compared against future HEVs and BEVs.
- Additional guidance on peak power and onboard hydrogen needs will be useful. Additional understanding of the comparison of FCEV costs to the costs of other vehicle platforms, including conventional vehicles and hybrids, will be useful. It is unclear what the need is for higher fidelity plant and cost modeling, partly because it is unclear what the limitations are on the cost assessment embedded into the findings in the project thus far.

Project strengths:

- Use of the Autonomie model, which has been well vetted and is a well-regarded model for advanced vehicle simulations, is an excellent approach to understanding fuel economy improvements from advancements in fuel cell stack efficiency. Analysis of a range of vehicle classes and sizes and comparison to other vehicle types, such as conventional gasoline vehicles and HEVs, helps provide a better understanding of how FCEVs perform in relation to competing vehicle technologies. The analysis provides a very good understanding of the impact of fuel cell stack efficiency improvements on FCEV fuel economy across a range of vehicle sizes and classes. The findings of how fuel cell stack efficiency improvements lead to improvements in vehicle weight associated with the reduction in the need for hydrogen storage and other subsystems are significant and help show how fuel cell stack improvements lead to overall FCEV system improvements.
- Analytical tools and stakeholder interactions are excellent.
- The project team has a lot of experience in vehicle modeling. Autonomie is a strong model.

Project weaknesses:

- The project may benefit from additional collaboration with industry stakeholders to improve cost and performance information, though it is unclear how much of this information from consultations with industry is embedded into the Autonomie model. It is unclear what the limitations are on the cost modeling in the findings to date (the presentation notes the need for more detailed cost modeling).
- The project should compare the project’s subject technologies to tomorrow’s advanced vehicles, such as Tesla and HEVs.
- The project could benefit from more frequent reviews from stakeholders to improve the presentation and clarity of the results, but the project itself is very well done. There is no information about the “experts” consulted.

Recommendations for additions/deletions to project scope:

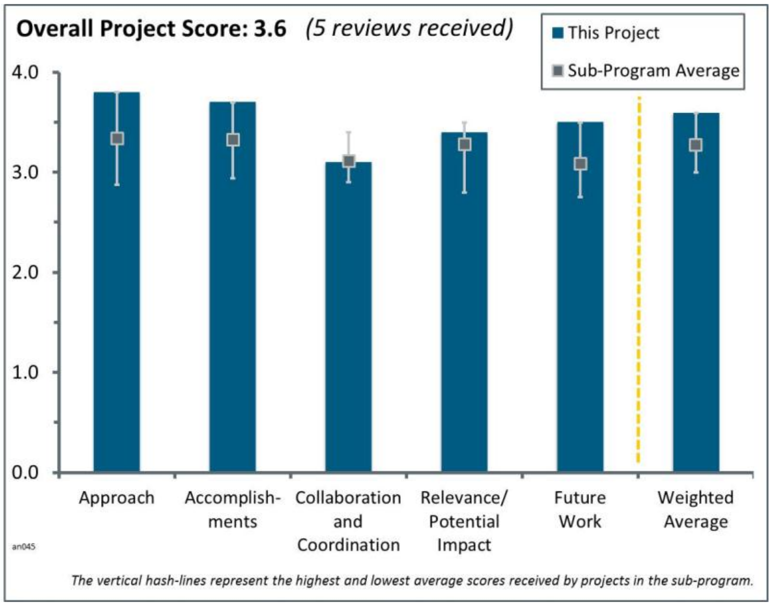
- It would be good to see more analysis like this—possibly expanded to provide projections for different vehicle classes, including heavy duty vehicles.
- This effort should be continued with hybrids. Feedback comments should be provided from U.S. and overseas fuel cell and hybrid developers.
- The description of the scenarios and cases could be improved by adding a slide with definitions. The project should explain some of the results seen in the tables. For instance, the numbers in slide 39 do not seem to make much sense—the dollar figure is higher in the "average" cost scenario than in the "high" cost scenario. An explanation of the results in the table would be useful. The same problem occurs in slide 41. The hydrogen tank cost "decreases" at higher efficiencies, not the other way around. The work is very strong, well executed, and technically solid, but it does not add much to the existing body of science. HEV and BEV should be added to the analysis.

Project # AN-045: Analysis of Incremental Fueling Pressure Cost

Amgad Elgowainy; Argonne National Laboratory

Brief Summary of Project:

The overall objective of this project is to provide a platform for comparing the impact of alternative refueling methods and fueling pressure on the cost of dispensed hydrogen. The impact of fueling pressure on the fill rate and refueling cost is evaluated. The modeling of hydrogen refueling stations (HRSs) incorporates the implications of the SAE International J2601 refueling protocol. Cost drivers of various fueling technologies and configurations are identified, and the potential of novel concepts to reduce refueling cost is evaluated.



Question 1: Approach to performing the work

This project was rated **3.8** for its approach.

- Development of the Hydrogen Station Cost Optimization and Performance Evaluation (H2SCOPE) model for optimization of compression, storage, and dispensing components provided an excellent approach to understand and consistently analyze hydrogen storage and dispensing configurations. The approach for conducting H2SCOPE model development based on physical laws and properties that were then validated against experimental data was excellent. The project provides a better understanding of hydrogen delivery and dispensing costs, particularly in reference to developing cost estimations for various hydrogen dispensing pressures.
- The development and the modeling structure in combination with key vehicle tank properties and existing refueling protocols provides an excellent approach to this project.
- The principal investigator has done excellent work as usual. This is how the reviewer would have approached the project.
- The principal investigator has taken a reasonable, well-planned approach to address numerous issues surrounding fueling pressure.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.7** for its accomplishments and progress.

- Development of the H2SCOPE model for hydrogen dispensing optimization and system configuration provides an excellent tool for understanding hydrogen station components and configurations. The H2SCOPE model was based on physical laws and properties and has been validated against published experimental data. The project provided excellent data on station costs and configurations to support various hydrogen fill times, including important information on hydrogen pre-cooling needs. Development of hydrogen compression, storage, refrigeration, and dispensing components is critical for improved hydrogen cost modeling. The project provides a thorough understanding of the cost of station components and the resulting hydrogen cost for hydrogen dispensed at various pressures to fuel cell electric vehicles.
- Significant accomplishments achieved by this project include the development of the H2SCOPE model and the evaluation of relaying time at different pre-cooling temperatures. These accomplishments will provide

very valuable information in understanding the impact of different hydrogen refueling pressures and the optimization of it.

- The assembly of a wide variety of data describing the various trade-offs around fueling pressure has been carried out thoroughly, and results were presented clearly. The H2SCOPE model is a major accomplishment that allows proper sizing and optimization at fueling pressures of interest. Results show potential for precooling at -30°C rather than -40°C. This could be a significant savings for forecourts. The graphs illustrating the wrap-up into final fueling costs show the pressure effects well.
- The material was processed and presented in a very professional and succinct manner.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.1** for its collaboration and coordination.

- There is good work with manufacturers of compressors, refrigeration equipment, and others to acquire and analyze both performance and cost data.
- The collaboration with vehicle original equipment manufacturers (OEMs) and with hydrogen station equipment suppliers is key to the progress of this work.
- The project included very good collaboration with other national laboratory researchers, industry (through the U.S. DRIVE Partnership), and component supply companies. More in-depth collaboration and consultation with additional hydrogen component supply companies (and supply companies for other related industries, such as natural gas storage and dispensing equipment manufacturers) would aid in ensuring that the projected cost of hydrogen station components is accurate and reflects the variability of component costs across the industry.
- It would have been good to have more collaboration—it was not obvious that input was taken from compressor companies, for example. There are nonlinearities due to compressor availability—especially in the short term. For example, the type of compressor would be different past certain pressure thresholds (e.g., bootstrapping of last compression stage). This may push conclusions of the analysis to favor lower pressures.
- The project should spend some more time seeking input and distributing information to actual station designers, owners, and operators.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- The project enables a better understanding of potential hydrogen station configurations and the cost of hydrogen station components, which will help improve dispensed hydrogen costing models. The project provides a more thorough understanding of the cost of dispensing hydrogen at various pressures, which may aid DOE in understanding how to develop an adequate network of hydrogen refueling stations given a fixed amount of investment capital available, particularly in the initial rollout years for infrastructure deployment.
- The relevance is high, but ultimately DOE might have little leverage over OEM decisions for optimal pressure. The project provides understanding for public consumption and some possible consensus views for OEMs to consider (in case they have not done their homework).
- The understanding of pre-cooling requirements at hydrogen stations and the impact on the cost of station refueling equipment are definitely addressed with this project.
- OEMs appear to have settled on 700-bar fueling, so these studies, while well done and scientifically relevant, may not have an impact on the marketplace.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- Updating the Hydrogen Delivery Scenario Analysis Model (HDSAM) delivery cost model with the findings of this analysis will ensure a more accurate modeling of dispensed hydrogen cost. Integration of the H2SCOPE model with HDSAM to better optimize hydrogen station configurations will improve our understanding of hydrogen costs. Investigations of liquid hydrogen delivery components are a good extension of this work.
- Updating the analysis work with the latest version of SAE International J2601 and the MC refueling method will provide very valuable information to this project.
- Trade-off work with refrigeration and heat exchangers is a good addition. The HDSAM update is needed and should be pursued.
- It would be good to see much more collaborative activities with compressor companies, e.g., PDC Machines.

Project strengths:

- The project enables a better understanding of potential hydrogen station configurations and the cost of hydrogen station components, which will help improve dispensed hydrogen costing models. The project provides a more thorough understanding of the cost of dispensing hydrogen at various pressures, which may aid DOE in understanding how to develop an adequate network of hydrogen refueling stations given a fixed amount of investment capital available, particularly in the initial rollout years for infrastructure deployment. Development of the H2SCOPE model for hydrogen dispensing optimization and system configuration provides an excellent tool for understanding hydrogen station components and configurations.
- This project appears to have some potential to provide practical advice to station designers and is therefore a good project. Any added demonstration aspect would be a nice added benefit.
- The competent analysis and state-of-the-art filling model are strengths.

Project weaknesses:

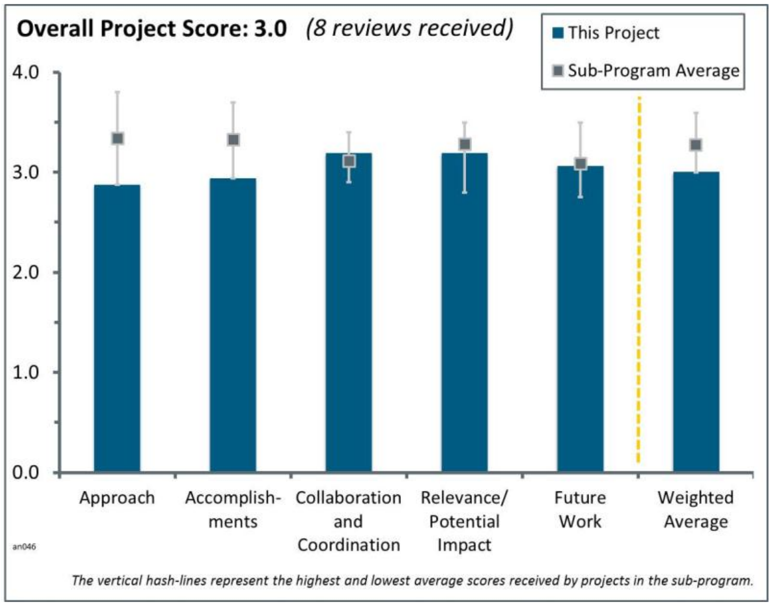
- More in-depth collaboration and consultation with additional hydrogen component supply companies would be useful and would aid in ensuring that the projected costs of hydrogen station components are accurate and reflect the variability of component costs across the industry. Supply companies for other related industries, such as natural gas storage and dispensing equipment manufacturers, may yield useful cost information for components.

Recommendations for additions/deletions to project scope:

- The project should consider asking compressor makers about the impact of pressure on reliability.

Project # AN-046: Hydrogen Station Economics and Business (HySEB)—Preliminary Results

Zhenhong Lin; Oak Ridge National Laboratory



Brief Summary of Project:

The overall objective of this project is to develop a tool to analyze profitability, risk, and public–private partnerships in hydrogen station deployment. The Hydrogen Station Economics and Business (HySEB) model optimizes key deployment decisions to maximize profitability in consideration of investment risks, employing a clustering strategy.

Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- The project addresses three barriers: (1) future market behavior, in that it will suggest where to site new hydrogen fueling stations; (2) stove-piped/siloed analytical tools, in that it will combine a number of models and tools across a number of analytical platforms; and (3) insufficient models and tools, in that it will provide a new model based on existing tools and potentially a model validation tool as well.
- The use of cumulative cash flow is a good approach because it is one that investors can easily assess and use. The "Next-N-years" net present value (NPV) concept was confusing. NPV is usually a single value. The principal investigator needs to use metrics that are commonly used in the investment community and make the presentation more comprehensible. Rather than use the Next-N-years NPV metric, the investigator should clearly state, "Given a government subsidy of $X for Y years, the NPV of the project is $Z." Penetration rates based on projections are fine, but the market should also be modeled using both hybrid and plug-in hybrid electric vehicle penetration rates for comparison.
- The use of the station costs and clustering strategy from previous work at the University of California–Davis (UC-Davis) as the assumptions to their modeling work, in addition to the use of Hydrogen Analysis model (H2A), is a very good approach to address the main objectives of this project.
- So far we see the approach for trading off between emphasizing larger or smaller stations. There is concern that there is more to the story—for example, the model appears to have static stations. In reality, as demand grows, stations will expand to conform to demand. The question might be better stated to include an upgrade strategy rather than a strategy that places only new stations into a region. It is good to see leveraging of existing analysis—such as from UC-Davis.
- Analysis of a clustered station deployment is appropriate for the initial rollout of hydrogen refueling infrastructure. Analysis of different driving patterns and behaviors strengthens the analysis. It is unclear what assumptions and parameters are embedded into the HySEB model, and it is unclear whether the model has been thoroughly validated and peer-reviewed. It is unclear what assumptions were made regarding hydrogen station costs. The presentation lists costs as coming from a 2013 publication from Dr. Joan Ogden and from the H2A model. The H2A model is a costing tool that provides the cost of hydrogen on a dollars-per-kilogram basis given the input cost of hydrogen station capital—it is unclear where these station costs came from or if the costs are associated with particular published H2A case studies.
- The main weakness with the work is that the results are difficult to interpret or compare. It would be better if there was a simple definition of the objective function that the consumer/investor should seek to optimize. This should be the output of the model.

- The project goals are too broad and may be difficult to fully satisfy without broader engagement and participation of key industry stakeholders. Absent from the analysis is the amount of private and public support required to financially support the development of hydrogen fueling infrastructure proposed. It is good to see that the U.S. Department of Energy (DOE) is evaluating the merit of public–private partnerships as a means to develop early market hydrogen infrastructure. Considering public–private partnerships can be quite diverse, the "term-limited" public–private partnership evaluated in the analysis will face difficulties with private companies and individual investors because of the long buy-down period in the analysis.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **2.9** for its accomplishments and progress.

- Good preliminary results have been presented on this project, mainly in providing the analysis of how combining a cluster strategy with station-scale economy and travel patterns could significantly affect the system cost.
- The analysis provides information and findings on how station size and deployments can affect NPV, including analyses of different driving patterns. The analysis and findings are based on the HySEB model, which was developed for this project. The findings would benefit from peer review of the analysis and, in particular, a peer review of the HySEB model. It is unclear what assumptions are embedded into the HySEB model, and it is unclear either how the HySEB model incorporates the information from other DOE and academic modeling (Scenario Evaluation, Regionalization, and Analysis [SERA], Hydrogen Delivery Scenario Analysis Model [HDSAM], H2A, and the Spatially & Temporally Resolved Energy & Environment Tool [STREET]) or how HySEB compares to these models if it does not incorporate data from them. The findings of this analysis would be strengthened if the underlying model parameters and assumptions could be compared to existing modeling on hydrogen cost, station cost, and infrastructure siting.
- A new model (HySEB) has been developed to understand the economics of hydrogen fueling stations. Some preliminary results were presented that suggested that this analysis will be useful, but the modeling needs to react to the developing picture on the ground as stations are added, i.e., it cannot be using yesterday's situation to predict tomorrow's future.
- The analysis is very exploratory in nature, but the HySEB model appears to be already institutionalized. Considering that this is a new project, it is too early to place HySEB in the same category as other DOE and national laboratory models that have been fully vetted and developed over many years. One of the project goals is to address stove-piped/siloed analysis. Because public–private partnerships are not new and have been exercised across other industries and markets, perhaps a proven public–private partnership arrangement structure already exists that can be applied to hydrogen infrastructure.
- It was somewhat hard to tell what has been accomplished from the presentation. It appeared that a new model, HySEB, had been developed. However, it would be good to see a bit more time spent looking critically at the inputs to that model and the sensitivities of those inputs. The inputs were overly optimistic and based on a single analysis. Building the framework of a model is part of a modeling project, but the more important aspect is vetting the data inputs. That is arguably where the bulk of the work should be spent, and it is not obvious that much work has been done here.
- As it is a new project, we have not seen the approach considered for future work items. As the project end date is October 2014, it is not evident that there is sufficient time to perform those additional tasks.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.2** for its collaboration and coordination.

- The authors have collaborations with both industry (Ford) and academia (University of Tennessee). There also was evidence of heavy collaboration within the national laboratory circuit. This is good and definitely helps to overcome the barrier of siloed analytical capabilities. Because the analysis is heavily dependent on

an economic analysis and it was unclear whether this is being done, it would be good to see more economists involved from academia.
- There is very strong collaboration for this project with a great combination of academia, national laboratories, and automotive industry.
- The project notes significant collaboration across national laboratories, government agencies, academia, and industry.
- The project works with a good mix of university, national laboratory, and industry collaborators. As is always the case with these projects, the more input the better, but the project has made an excellent start.
- The project includes good collaboration with very well-respected project partners. To ensure private sector buy-in, project collaboration needs to expand to a broader representation of industry stakeholders.
- More collaboration would be useful with vehicle original equipment manufacturers (OEMs) and infrastructure providers. Stakeholder points of view will add relevance. It will also be important to see what financial performance metrics are of interest to stakeholders.
- Collaboration with H2USA is required, given it is developing a cost model as well. This might be much more highly utilized than this model. It would be good to have the nice work done here incorporated into the H2USA work.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.2** for its relevance/potential impact.

- This is critical work—and it could not yield results too early. As investments are already in the works for infrastructure (e.g., California), feedback to inform station sizing trends will be critical. Any optimization that can improve station economics will reduce public subsidy needs and reduce investment payback time.
- The project is aligned with the DOE Fuel Cell Technologies Office's Market Transformation sub-program to help implement hydrogen fueling infrastructure in a real market environment. It is to be hoped that the project can address a solution to the inadequate level of federal incentives available to date for pre-commercial and commercial hydrogen infrastructure for light-duty vehicles.
- It is critical that DOE understands the real business situation on the ground and the number of subsidies and how long these must be applied to enable early adopters to be successful.
- This type of analysis work is key to the initial rollout of hydrogen station deployment and the economics around deployment.
- The link this analysis was making towards advancing the goals of DOE was not clear. It was potentially an interesting analysis, but more thought needs to be put into justifying how this will be useful to the overall goals. In other words, it needs to be made clear who will use this and how they will use it. Then, what overall benefit it will have needs to be indicated. Part of the issue stems from the fact that the metrics are not very clear, and there is no obvious way to compare the different options or to compare with a baseline case.
- The project helps with understanding the investment needs for initial hydrogen infrastructure rollout, including the level of public–private partnership required. The analysis helps provide an understanding of the needs and uncertainties associated with the initial deployment of hydrogen infrastructure. It is not clear whether the modeling provided by HySEB adds to DOE's understanding of hydrogen station cost and infrastructure rollout or whether HySEB is a new modeling of cost and infrastructure siting that does not reflect previous work conducted by DOE.
- There is uncertainty about the relevance if the project is not collaborating with the H2USA working group.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work outlined by the researcher should provide additional value to the preliminary results obtained so far on this project.
- The topics are relevant next steps of this analysis.

- The project includes a good amount of future work, and the future project work needs to be prioritized. More analysis of public–private partnerships' cost-sharing mechanisms should be a top priority because it may eliminate the need for future work in other areas. One concern is that institutionalizing HySEB too early may risk the chance of abandoning the analysis in the future.
- It would be beneficial to have more alignment of the model with experiences of other fuel station systems, with incumbent/conventional technologies. It might be possible to do this through collaboration with companies that manage stations or invest in stations.
- Future work will expand on preliminary data; the project needs to be careful about sensitivity analysis and uncertainties in this new market.
- The proposed future work would be useful, but it appears ambitious considering the budget and remaining time left for the project. Future work should include further validation of the HySEB model, which the analysis and findings rest upon, and a peer review of the HySEB model would be particularly useful.

Project strengths:

- Analysis of a clustered station deployment is appropriate for the initial rollout of hydrogen refueling infrastructure. Analysis of different driving patterns and behaviors strengthens the analysis. The project includes significant collaboration across national laboratories, government agencies, academia, and industry.
- Collaboration seems to be the strength of the project. Many parties appear to be actively involved. It would be good to see this continued.
- The project begins to give an idea of how the economics of hydrogen fueling stations will play out.
- Credit should be given toward the evaluation of public–private partnerships as a potential means to develop early market hydrogen infrastructure.

Project weaknesses:

- The weakness is mostly that the product is difficult to use or interpret. If some time is spent clearly defining this, the project has potential.
- Dealing with the uncertainties while giving a realistic picture to guide policy and incentives needs to be handled realistically.
- The basic public policy partnership structure options should have been initially explored. Preliminary data analysis and presentation should be simplified for the introductory project presentation.
- The findings would benefit from peer review of the analysis and particularly from a peer review of the HySEB model. It is unclear what assumptions are embedded into the HySEB model, and it is unclear either how the HySEB model incorporates the information from other DOE and academic models (SERA, HDSAM, H2A, and STREET) or how HySEB compares to these models if it does not incorporate data from them. The findings of this analysis would be strengthened if the underlying model parameters and assumptions could be compared to existing modeling on hydrogen cost, station cost, and infrastructure siting.

Recommendations for additions/deletions to project scope:

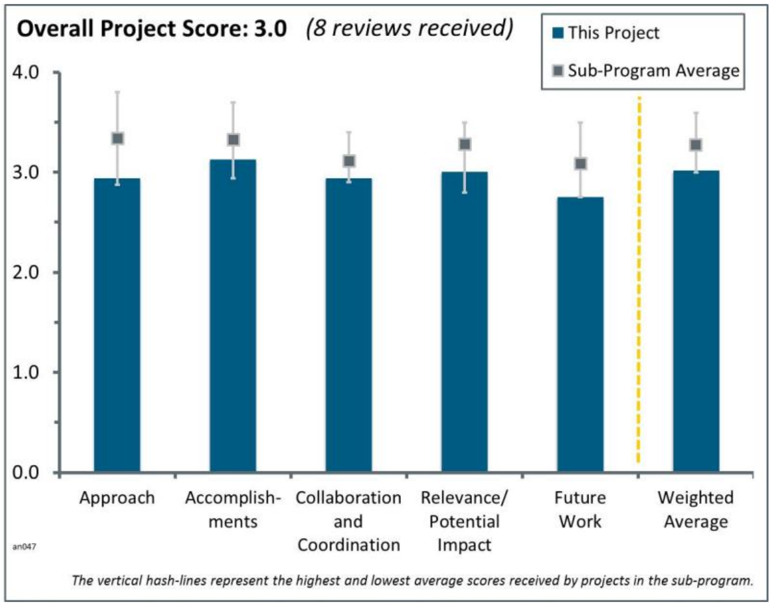
- Station upgrading strategies with demand growth should be considered.
- The project should obtain more feedback from new stations as they are deployed.
- The project introduces a new financial concept that requires more clarification and understanding. Graphs throughout the analysis are very "busy," and the differences between the analyses of the various buy-down periods are not clear. The "valley of death" between the small, medium, and large stations should be more transparent and built into the hydrogen station timeline. The analysis promotes a policy that incentivizes a guaranteed buy-down value over a period of time and will naturally incentivize larger and more expensive hydrogen stations. It remains questionable if that is really the right approach to building national hydrogen infrastructure for a fuel cell electric vehicle market that will take many years to realize an appreciable level of market penetration.

Project # AN-047: Tri-Generation Fuel Cell Technologies for Location-Specific Applications

Brendan Shaffer; University of California, Irvine

Brief Summary of Project:

The objective of this project is to assess the potential number and location of tri-generation (tri-gen) fuel cells producing electricity, heat, and hydrogen in an early fuel cell electric vehicle (FCEV) market scenario (circa 2015) in New York, New Jersey, Connecticut, and Massachusetts. The analysis considers the use of natural gas (NG) and anaerobic digester gas as feedstock. It also considers the viability of the tri-gen units serving as a local hub for hydrogen production.



Question 1: Approach to performing the work

This project was rated **2.9** for its approach.

- This is a well-designed and comprehensive view of the issue. The author has drawn from a wide variety of data sources to bring together a model that gives a clear picture of the challenges that may face tri-gen plants at renewable biogas locations. The project plan, design, and sources are clearly laid out. The objective to compare different types of tri-gen facilities is clear. The approach addresses all barriers.
- The project has a good approach and good ideas. It could be improved by adding a more realistic estimate of demand at sites based on vehicle miles traveled. Likely this will not change the fact that potential owners neither drive nor live near tri-gen facilities. Likely the heating load is a more binding constraint, as fuel may be transported to nearby stations that do have pass-by demand. Additional incorporation of underlying economic factors will add value.
- The approach employed seeks to overlap map locations of vehicle sales with wastewater treatment (WWT) sites and landfill sites as potential sites for feed gas for tri-gen of heat, electricity, and hydrogen (for future FCEVs). The approach of overlaying maps is an interesting visual technique to identify sites; however, the approach adopted is limited in its assumption that current sales of alternative fuel vehicles are an accurate predictor of future FCEV sales. The approach appears to be limited in flexibility—it focuses solely on tri-gen (heat, electricity, and the use of hydrogen for FCEV). If the approach loosened (e.g., to look at other sources of fuel, such as pipeline NG), the number of sites for tri-gen would increase dramatically. It was not made clear if the project was specifically constrained to wastewater, landfill, and FCEV attributes. If the intention was to show how to identify sites for tri-gen, then limiting them to a narrow set of constraints does not do justice to identifying the broader range of capabilities for tri-gen.
- There are good partners from the automotive developer side. There is good information on WWT and landfill gas (LFG) sites. Matching of heating and cooling loads is a good criterion. Partners from tri-gen developers will strengthen the study. The use of waste heat is another missing link in approach. The project needs to justify California versus the Northeast. The Northeast needs energy security also—post-Hurricane Sandy.
- The approach is reasonable. Linking geographic information systems (GISs) and alternative fuel vehicle sales to assess landfill sites and potential tri-gen locations is good. Use of alternative fuel vehicle data as currently implemented is problematic. The household income threshold of $75,000 as an indicator of the likelihood of being a FCEV early adopter is quite dubious. This number should be much higher. Perhaps the project could use family income as an alternative indicator. The application to the New York

metropolitan area is good (i.e., it is good to expand beyond just a California analysis as so many past analyses are focused).

- This is early in the project, and it is suspected that the investigators have not settled on their methodology. The current methods are very approximate. Heat loads for sites are not yet available. There is apparently no consideration of transporting the hydrogen from the site where it has been generated, even for short distances and even for mobile refueling equipment (this is an early market study). This is especially important because, as the investigators note, landfill and WWT plants are not typically good locations for refueling stations.
- Highly detailed, spatially resolved modeling efforts have questionable value when the economics of tri-gen operations are highly uncertain. Early adopters who can afford FCEVs are unlikely to get excited about driving to a landfill or water treatment site to fuel their vehicles. Hydrogen (or methane) from renewables (landfill and water treatment) is very costly and unlikely to be used in early markets. The analysis does not appear to have any assessment of resource size, i.e., how much methane/hydrogen the relevant landfill/water treatment facility can produce.
- Matching loads with potential sources of energy is a good idea, but it is unlikely that this project will get traction given that (1) state/local officials/permitting authorities (major stakeholders) have not been involved, (2) there have been no economic considerations included to calculate the economic disparity between the current system and the proposed tri-gen technology, (3) there is no calculation of the associated environmental advantages—it is important to calculate potential emissions/water consumption avoided—and (4) sources and consumer loads have not been matched. This study could use some additional collaborations to tackle the barrier of "siloed analytical capability," which is not being overcome with the current approach. Also, it is unclear how "future market behavior" will be overcome as a barrier with the current approach.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.1** for its accomplishments and progress.

- Given the stage of the project, the progress to date is excellent. However, there is a need for an improved analytical approach.
- Good progress has been made. It would be good to see more economic assessment to tackle the barrier of "future market behavior." It is not clear how local geographies affect the economic assessment of tri-gen facilities.
- There seems to be tremendous progress for only 3% of project spending. The project has a good start but clearly needs to modify parameters (e.g., the $75,000 income threshold) and expand the study. The project needs to better define how large a station is. The presentation links vehicle population numbers to the associated station requirements, but this link is based on a hidden assumption of station size.
- The identification of the top 10 WWT and LFG sites is very good. NG can support biogas—it is a good strategy. The results and strategy for addressing the stranded assets issue with FCEVs during the initial period are very encouraging. The connection between FCEV locations and these sites seems to be improper. Population density is a better parameter.
- Given the fact that the project just started (the kickoff meeting was in February 2014), the progress is appropriate.
- Goals are fairly broadly defined, so this question is difficult to answer. If the first half is mapping and the second half something else, then progress is excellent. If the mapping portion is done, then there is a little more to do on this front.
- The ability to serve stations appears to be based solely on sites within a given distance. It appears to ignore factors related to the quantity of hydrogen that a given landfill or water treatment facility can produce. Heating loads are generally seasonal. It is not clear whether this is incorporated into the data.
- Data were acquired and mapped relatively quickly. However, the infrastructure scenarios will be incomplete if the appropriate techno-economic analysis is not carried out. The loads dataset needs to be cleaned up—thresholds should be identified for heat and electricity consumption needed by a building/group of buildings for which it would be ideal to provide tri-gen. For instance, there could be buildings with 70% heat load and 30% electric load—it is not clear how to ensure that the loads are met optimally (i.e., cheaper than the incumbent alternative). That could take much work and additional effort. It is not clear whether this can be achieved within the time frame and scope of the project.

Question 3: Collaboration and coordination with other institutions

This project was rated **2.9** for its collaboration and coordination.

- Industry partner and national laboratory contributions demonstrate clear collaboration with key stakeholders in the hydrogen arena. Toyota's involvement will help future goals of incorporating vehicle sales into the analysis.
- Collaborators include the National Renewable Energy Laboratory (NREL) and Toyota (car sales), but there are not any collaborations with a tri-gen company.
- Coordination looks pretty good with industry partners, as well as with NREL.
- Collaboration appears to primarily be with NREL. However, the extent of the collaboration is difficult to assess.
- It is too early to tell, really. The reviewer hopes there will be more outreach to industry to broaden the range of the premises and business models considered.
- Collaboration could be improved by bringing additional stakeholders to the table, including local and state officials as well as the regulatory authority that permits power generation projects to identify siting constraints and potential technology supporters. It would also be good to get NREL's input on the economics of the project and the design of the production and dispensing facilities.
- The principal investigator needs to find collaborators that can furnish economic data.
- The project needs to collaborate with stakeholders in the Northeast such as the Connecticut Center for Advanced Technology (CCAT). Other users of hydrogen should be added.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.0** for its relevance/potential impact.

- The relevance is very high. As stated in the scope, renewable, low-cost hydrogen will be in high demand.
- This is an excellent beginning.
- The project is relevant to assessing the viability and effectiveness of bio-based tri-gen facilities. Coupled with a study on the economics, this project would be useful to determine whether these could compete with NG in selected locations.
- Finding out the potential role of tri-gen with hydrogen production for FCVs is important. It could be a valuable source of hydrogen during the early transition, but this kind of analysis is needed to inform the issue.
- The approach is interesting and makes good use of mapping data, and it provides a tool for identifying future sites for cogeneration and production of hydrogen.
- The project is identifying actual potential infrastructure scenarios for long-term transportation needs and early market opportunities, which aligns with the Multi-Year Research, Development, and Demonstration Plan. However, the impact and likelihood of success are low, given that there is no environmental or socioeconomic analysis and that the right stakeholders have not been involved to increase the likelihood of implementation.
- The work is significant to only one path. There is a high-cost biogas pathway, and it is unlikely to have an impact in early markets with high risks because of the uncertain market size. It should be considered only for mature markets where it is likely to be implemented. Without economic estimates, this work has little relevance to addressing FCEV introduction.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- Considering the size of the project, the activities are well defined and should be readily achievable.
- The goals seem pretty broad, so the future work looks flexible. It is not really clear what the future work entails, exactly. The research can go in any direction, but it is not clear what that is.

- More attention should be paid to the economics, as market behavior is a barrier being addressed. It is not clear what the cost is going to be in the different geographies.
- The project needs to give more thought to the premises concerning operation of tri-gen installations and the use of the hydrogen, especially whether it can be transported or loaded into mobile refuelers. The researchers need to consult with tri-gen equipment manufacturers and hydrogen suppliers on these issues.
- The first priority should be the incorporation of economics in the work. Until the economics are clear, the other issues are peripheral.
- The project needs to add hydrogen use for forklifts and grid support and other parameters—it is not clear whether there are fleet vehicles located near a big LFG and WWT plant.
- The future work looks okay, but it is missing elements.
- The description of future tasks lacks detail.

Project strengths:

- The project is very organized, and the approach is clear. Data gathering has been a clear strength as well, with a variety of sources being leveraged to come up with this model.
- The use of mapping data to identify energy sources (e.g., waste gas methane and LFG) and energy consumption (heat, hydrogen, and electricity) is excellent.
- The project makes good use of geographic data and the Spatially & Temporally Resolved Energy & Environment Tool (STREET) model.
- The project has a reasonable approach that will lead to interesting results. The team seems to be applying the correct/useful tools to the analysis.
- This is a great idea to start with tri-gen. The project should have more stakeholders from the Northeast provide input, including an assessment of how quickly stations can transition to profitability—sell power to the grid or a WWT plant.
- Good GIS modeling capabilities are present. Energy loads and locations of potential sources of clean hydrogen are available.
- The subject is good. It is generating potentially important results. The project is led by those with direct experience in the tri-gen field.

Project weaknesses:

- The $75,000 income threshold is a dubious filter value.
- There are no economics.
- The constraints associated with the fuel source (landfill/waste gas versus pipeline gas) limit the siting and potential market for the tri-gen concept.
- The project should address capacity utilization as an added parameter. WWT and LFG can support over 100,000 FCEVs. The team needs to double check its math. The heat load of WWT plants should be considered. Perhaps the project should involve General Motors, FuelCell Energy, CCAT, Rutgers, etc.
- State and local officials (major stakeholders) have not been involved. There have been no economic considerations to calculate the economic disparity between the current system and the proposed tri-gen sites. There is no calculation of the associated environmental advantages—it is important to calculate potential emissions/water consumption avoided. Sources and consumer loads have not been matched.
- To truly do this analysis right, a more complete incorporation of economics is needed. A more explicit representation of the limitations of the analysis is needed. The team needs to know what the analysis does well, what it needs, and what will it never do. There are aspects outside the scope that the project will never fully answer, but these things need to be explained or addressed in some fashion. Because the progress so far has been in mapping, a better representation of demand should be incorporated. Also, if the team is using any numbers from the census, they should look at the $150,000+ numbers for early market launch.

Recommendations for additions/deletions to project scope:

- This is a great project. Having input from the NG industry, WWT, and LFG is recommended. The use of waste heat from external sources can improve siting economics of tri-gen systems and increase the speed of payback.

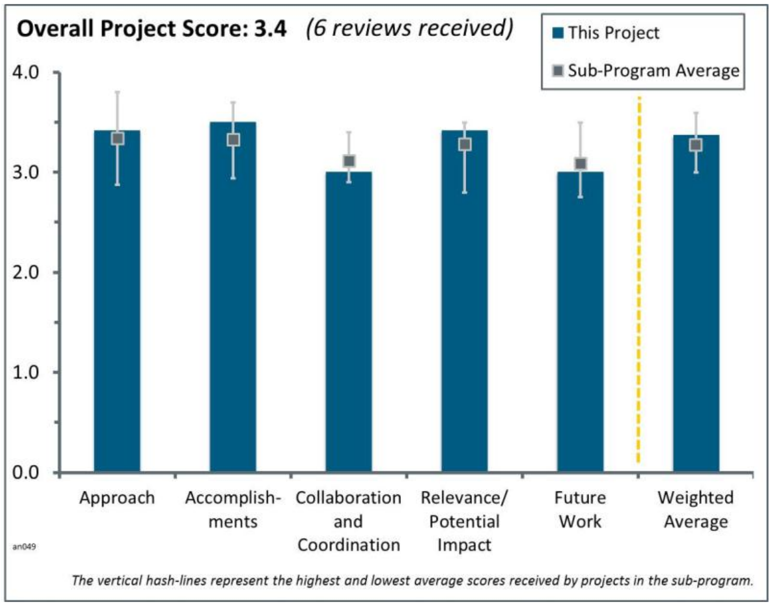
- The project should loosen up the constraints and consider pipeline sources of NG. The project should also consider increasing the six-mile-drive-time service coverage to ten miles—using this as a sensitivity variable.
- The project should consider transporting hydrogen by tube trailer or direct loading into mobile refuelers. The project should also consider short distance movements to better locations, in general.
- An economic analysis should be added, as should an assessment of the hydrogen production capacity of landfills and WWT.
- The project should involve regulatory authorities and local/state officials to provide input. Economic considerations should be included to calculate the economic disparity between the current system and the proposed tri-gen technology. The associated environmental advantages should be estimated—it is important to calculate the potential emissions/water consumption avoided.
- The project should do the following: consider hub arrangement for hydrogen generation and use; include more specifics in future plans; raise the $75,000 income threshold; quantify the levels of heating load; and assess the cost and the feasibility of various distances of heating sources to hydrogen generation (i.e., potential heating/electrical loads are listed at various distances from the landfill, but it is not clear at what distance it is cost-prohibitive).
- The project should add more on the systems-level analysis of the tri-gen systems. The costs and benefits of different sizes of systems are not clear. It is not clear what can we learn from the existing University of California–Irvine tri-gen system and what is transferable.

Project # AN-049: Electricity Market Valuation for Hydrogen Technologies

Joshua Eichman; National Renewable Energy Laboratory

Brief Summary of Project:

This work explores future market opportunities for hydrogen technologies and expands modeling capabilities for integration with the grid. The objectives of this project are to evaluate the ability of electrolyzers to bid into electricity markets, to assess the value proposition for grid integration of hydrogen technologies, and to include hydrogen technologies into large-scale grid operation models.



Question 1: Approach to performing the work

This project was rated **3.4** for its approach.

- The study was exceptionally well done. Appropriate methods were used to evaluate the potential for profitable operation of electrolyzers producing and selling (or not selling) hydrogen, providing grid services (or not), etc. The results provide clear guidance on the prospects for integrating electrolyzers with the grid while producing hydrogen for sale to the transportation market.
- The approach of the model was clear, and in particular, the authors' ability to convey the objectives of the project in a concise and logical manner was impressive.
- The project is well organized and logical. The objectives are particularly well stated.
- Introducing hydrogen production technologies into the electricity market is an interesting option to generate a revenue stream, particularly during the early stages of fuel cell electric vehicle (FCEV) penetration. The approach addresses all the barriers described. The approach would be even more interesting if it incorporated a trade-off analysis of hydrogen technologies versus incumbent technologies. Also, solid oxide fuel cells (SOFCs) could be analyzed. Bloom Energy has 50/100/200 kW commercial fuel cells that could be used for non-spinning reserve and/or supplemental reserve.
- The use of electrolyzers for frequency support is a good near-term opportunity.
- The project effectively established and validated water electrolysis efficiency for polymer electrolyte membrane (PEM) and alkaline electrolysis through equipment testing at the National Wind Technology Center (NWTC). Credit must be given that the analysis results of the energy supply concept were not compared to the full gamut of energy storage options. In a thorough review of the analysis, the results contain a high level of uncertainty.

Question 2: Accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals

This project was rated **3.5** for its accomplishments and progress.

- There is good progress. Results are surprising and insightful. However, it would be good to see how the technologies compare against an integrated gasification combined-cycle (IGCC) turbine or a single-cycle turbine in terms of economics. This project proposes a potential solution to the revenue issue being faced by hydrogen production technologies.
- The project has made good progress and has already developed some clear conclusions. It would be good to see a bit more work on the inputs of the model. Currently, it appears to be more like a sensitivity study, and

it would help to have a better feeling of realistic values based on other models at the National Renewable Energy Laboratory (NREL) that output these values.
- There is nice overall work in establishing an analysis framework to analyze hydrogen storage markets. It may be good to pare down the technology architecture to the highest-value market, which may be very valuable for DOE to understand at this early concept stage.
- The results of this study should lead to demonstrations and eventually to deployment.
- There are good modeling results.
- The project has produced a large body of analysis results. Proof of electrolyzer flexibility is largely asserted rather than proven by analysis/testing. The backup slides offer some values but are not well explained. Also, only some modes of electrolyzer flexibility were tested, with other aspects being out of work scope. The project should more clearly identify the relative value of each mode of flexibility to ensure that data are collected on the most cost-effective aspects. The bar chart graphical display showing the range of costs for each configuration is very effective in conveying the complex modeling results.

Question 3: Collaboration and coordination with other institutions

This project was rated **3.0** for its collaboration and coordination.

- The project has good partners and uses resources well.
- The project included dialogue with electric power and water electrolysis stakeholders.
- The principal investigators involved a number of good stakeholders, but it would have been good to see more regulators and potential adopters involved from the beginning to generate additional feedback and improve the likelihood of technology adoption. Another potential collaborator could be a manufacturer of voltage control devices (e.g., static volt–ampere reactive [VAR] compensators, static synchronous compensators [STATCOM], etc.).
- Collaboration appears to be primarily briefing results after the analysis has been completed. Perhaps earlier interaction occurred, but it does not show up in the presentation. Also, collaboration is more than just briefing results; it must also include incorporating feedback into the analysis. There is no specific evidence that this occurred.
- Collaboration is not a big part of this study.
- This is probably the weakest point of the project. Although the material has been "presented" to stakeholders, it would be beneficial to see more involvement by stakeholders in the development of the model. The project should move from an after-the-fact review to getting input up front from stakeholders on how the model should be designed.

Question 4: Relevance/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan

This project was rated **3.4** for its relevance/potential impact.

- The conclusion offered thus far, that it makes sense to have electrolyzers participate in the grid, is valuable. The further clarification that electrolyzers offer advantages for things such as frequency control and response time is useful. Finally, knowing that integration in the grid makes sense only if the hydrogen is being sold helps to guide future research.
- The study makes an important contribution by demonstrating how the responsiveness of electrolyzers allows them to provide the full range of grid services and that this adds substantial value that could be used to significantly lower the cost of hydrogen produced by electrolyzers.
- Using hydrogen for transportation and extending its use is a win-win. It will help reduce hydrogen costs for all applications.
- The project effectively leveraged the capabilities and resources available at NREL and linked new potential technology to current and future energy markets.
- Introducing hydrogen production technologies into the electricity market is an interesting option to generate a revenue stream, particularly during the early stages of FCEV penetration. The topic is relevant to a

number of stakeholders, and it could even help with the integration of other renewable energy technologies such as wind turbines by providing the necessary ancillary services to the grid.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- It would be good to see additional future work to explore the feasibility of the concept, including a proof of concept. Also, it would be good to see how these technologies compare against incumbent technologies that serve the same purposes.
- Publications should contain full disclosure of assumptions and sensitivity analysis on the results.
- The project needs to add other pathways—a tri-generation system can complement electrolyzers.
- It does not appear from the list of future work that this project is continuing further. The project team should look at how it can enhance this analysis and if it can further guide things such as the size of the system that would be integrated, etc.
- The proposed work is only generally described. Less than half the money has been expended, and two out of the three bullets for future work relate to writing reports/journal articles. The third bullet represents a potentially large body of work but is not described.

Project strengths:

- The project has appropriate methods and data. The strong study design is producing useful answers.
- The established analysis framework to study the integration of hydrogen production into the electricity grid is a strength.
- The team has a good understanding of the subject. The project addresses an important barrier—the poor economics during early introduction of FCEVs.
- The large analysis scope appears to be executed well.
- The modeling tools are a project strength.

Project weaknesses:

- The conclusions could be stronger and more clearly stated.
- The project needs to add the International Organization for Standardization (ISO) and the Federal Energy Regulatory Commission as stakeholders. Monetization of ancillary services is needed.
- The project needs additional input from potential adopters. It needs more analysis of other technology options. There is little information on large-scale electrolyzers.
- This early stage type of analysis requires more transparency on the underlying assumptions. There are many elements of this project that are not clear: (1) the selling price for power returned to the electrical grid; (2) the price mix assumptions for hydrogen injected into pipelines, dispensed to fuel cell vehicles, or sold to industrial processes; (3) what the market mix is; (4) the power cost to run the electrolyzer; (5) whether the duty cycle for the electrolyzer is 24/7 or off-peak; and (6) whether the water electrolysis unit operates on 100% renewable energy or a combination of wind and grid mix. The cost contained in the project analysis was limited to water electrolysis production unit, storage, and installation costs. Additional costs associated with hydrogen compression and grid integration in providing ancillary services can add significant costs to a business concept and have a material impact on the overall results. It is very difficult to conceive that a hydrogen production system of a mere 500 kg/day capacity can cost-effectively be integrated into multiple markets.

Recommendations for additions/deletions to project scope:

- This is great work. The project needs to add California and Hawaii scenarios—look at what the problems are in the grid, how they are currently being handled, and how hydrogen pathways can improve them.
- The project needs to know the potential size of the market. It is not clear how much hydrogen could be produced in this way.

- Commercial success of this hydrogen supply concept is dependent on electricity price arbitrage, so results presented should include sensitivity analysis to reflect uncertainty and boundary-level results, especially because the PEM unit efficiency assumed in the analysis was 30% higher than results achieved at the NWTC test center; the price taker assumed ideal operation with perfect day forward forecasts.
- More analysis of the meaning of the cost results is needed. Some configurations are clearly not competitive. Others appear more promising and thus merit highlighting with further specification of how they might be implemented.
- SOFCs should be included. Bloom Energy has 50/100/200 kW commercial fuel cells. The project should be compared against other technology options to establish a baseline—this could include IGCC, single-cycle turbines, etc.