# IX.5 Sustainability Analysis: Hydrogen Regional Sustainability (HyReS)

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## Overall Objectives

- Develop a regional hydrogen sustainability analysis (HyReS) assessment framework that can be applied to hydrogen supply and fuel cell systems and is consistent with a broad range of existing sustainability assessment tools used by relevant stakeholders.
- Apply the framework as an enhancement to the existing suite of hydrogen systems analysis models developed for the U.S. Department of Energy's Fuel Cell Technologies Office (FCTO).
- Refine the framework to incorporate the latest developments in the field of sustainable development assessment, including recent data and analytic approaches, and to capture current issues relevant to key stakeholders.
- Implement the framework through a user interface that is accessible to target audiences, including private sector sustainability managers, industry stakeholders, government and non-government agencies, and potential investors.

## Fiscal Year (FY) 2017 Objectives

- Review existing sustainable development frameworks in order to identify and select metrics to be included in the HyReS framework.
- Develop case studies to quantify environmental burdens for a select number of hydrogen supply chains and the fuel cell electric vehicle (FCEV) life cycle, consistent with the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model and Hydrogen Analysis (H2A) production models.
- Explore how regionalizing parameters in the hydrogen supply chain impact life cycle results.
- Benchmark hydrogen case study results against comparable vehicle–fuel systems, including conventional vehicles, hybrid electric vehicles (HEVs), and battery electric vehicles with 400-mile driving range using only electricity (BEV400s).

## Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section of the FCTO Multi-Year Research, Development, and Demonstration Plan.

(A) Future Market Behavior

(B) Stove-piped/Siloed Analytical Capability

(D) Insufficient Suite of Models and Tools

## Contribution to Achievement of DOE Systems Analysis Milestones

This project will contribute to achievement of the following DOE milestones from the Systems Analysis section of the FCTO Multi-Year Research, Development, and Demonstration Plan.

- Milestone 1.19: Complete analysis of the potential for hydrogen, stationary fuel cells, fuel cell vehicles, and other fuel cell applications such as material handling equipment including resources, infrastructure and system effects resulting from the growth in hydrogen market shares in various economic sectors. (4Q, 2020)
- Milestone 2.2: Annual model update and validation. (4Q, 2011 through 4Q, 2020)

## FY 2017 Accomplishments

- Of 63 sustainability indicators identified through literature review, twenty-two will be directly modeled in the HyReS framework, and an additional 26 will be related and potentially estimated using the HyReS framework. Fifteen of the identified indicators will not be addressed by the HyReS framework.
- Developed an analytic framework that integrates Argonne National Laboratory's GREET model and the National Renewable Energy Laboratory's Scenario Evaluation and Regionalization Analysis (SERA), Automotive Deployment Options Projection Tool (ADOPT), and Future Automotive Systems Technology Simulator (FASTSim) models, updating results to reflect current model capabilities (Milestone 2.2).

- Evaluated environmental impacts of four hydrogen supply pathways (two natural-gas-based and two renewable-based) for FCEVs. The impacts were evaluated at both national and regional levels based on state electricity generation mixes.
- Compared impacts from the four FCEV case study life cycles to the life cycle impacts from conventional gasoline vehicles, HEVs, and a BEV400.
- Example calculations monetized the social benefits from greenhouse gas (GHG) reductions, air pollution reductions, energy security benefits, and water use reductions for each vehicle–fuel system replacing one million conventional gasoline miles.
- Documented methods and results in an annual report for peer review.
- Presented methodology and preliminary results at two international conferences.

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## INTRODUCTION

The Hydrogen Regional Sustainability (HyReS) project examines environmental burdens in a regional life cycle assessment approach that takes into account the economic and social aspects of hydrogen supply chains and FCEV production and operation. The HyReS framework enhances, extends, and complements the capabilities of a number of analytic models developed for the U.S. Department of Energy, including the GREET and SERA models [1,2]. The HyReS framework will also incorporate data and analytic capabilities from other models relevant to sustainability assessment, such as the Environmental Benefits Mapping and Analysis Program (BenMAP) and Co-Benefits Risk Assessment (COBRA) models developed by the U.S. Environmental Protection Agency (EPA) [3,4]. The integrated framework will address a number of sustainability metrics, such as greenhouse gas and criteria pollutant emissions, water usage, energy usage, and life cycle costs.

Progress to date has involved reviewing the sustainability literature to better understand how the HyReS framework can interface with and be useful to key stakeholders. The result is a set of proposed HyReS indicators. Analytic progress in developing the framework has focused on integrating environmental metrics from the GREET model, which have been used to develop four case studies for distinct hydrogen supply pathways. Integrating these case studies into the HyReS framework has highlighted the importance of assessing environmental impacts on a regional basis. Current analysis also provides example results of an approach to monetizing benefits (on a national scale) related to GHG emissions, air pollution, oil dependency, and water consumption.

## APPROACH

In order to assess regional sustainability impacts of hydrogen supply to FCEVs, HyReS relies upon an analytical framework that integrates the following capabilities: hydrogen demand based upon a detailed geospatial vehicle stock model (SERA) [2]; optimized, least-cost hydrogen infrastructure supply chain networks (SERA) [1]; life cycle fuel and vehicle impacts based upon GREET [5]; market adoption of FCEVs based upon the ADOPT model [6]; and a health benefits mapping and analysis of criteria pollutant emissions using, for example, BenMAP or COBRA [3,4]. Figure 1 provides an overview of FCTO targets, the integrated HyReS analytic framework, and key sustainability metric categories.

To demonstrate the effect of regionalization on the life cycle environmental impacts of hydrogen supply, four pathways are analyzed first on a national basis and then on a state basis. Differences across states are based on the 2015 estimated state electricity mixes, provided by GREET. Transportation distances and process efficiencies are also varied to test the sensitivity of results. The baseline results (assuming U.S. average grid mix) are then benchmarked against other vehicle–fuel systems. For this benchmarking, the Future Automotive Systems Technology Simulator [7] is used to simulate an electric vehicle with a test cycle range of 400 miles, where the lower real-world driving range would be comparable to that of an FCEV.

## RESULTS

The four hydrogen supply pathways considered in the preliminary case studies are gaseous hydrogen produced from natural gas and transported via heavy-duty truck (“GH2 from NG via Truck”), liquefied hydrogen produced from natural gas and transported via heavy-duty truck (“LH2 from NG via Truck”), gaseous hydrogen produced from poplar biomass transported via pipeline (“GH2 from Poplar via Pipeline”), and gaseous hydrogen produced from wind power and transported via pipeline (“GH2 from Wind via Pipeline”). For the baseline results the transportation distance, by either truck or pipeline, is 100 miles. Additionally, the baseline results are calculated assuming the U.S. average grid mix for electricity. Conversion efficiencies are, when necessary, altered from the GREET defaults to match those described in the Hydrogen Analysis (H2A) production models.

Figure 2 presents the baseline case study results for GHG emissions (g $CO_2$e/mi) and water usage ($cm^3$/mi) for each of the four pathways and for the vehicle cycle, hydrogen supply (well-to-pump), and vehicle operation (pump-to-wheels). The results indicate that the “LH2 from NG via Truck” pathway is associated with the highest life cycle GHG emissions. The difference in impacts from the two natural gas pathways is from the additional electricity for liquefaction. Compared

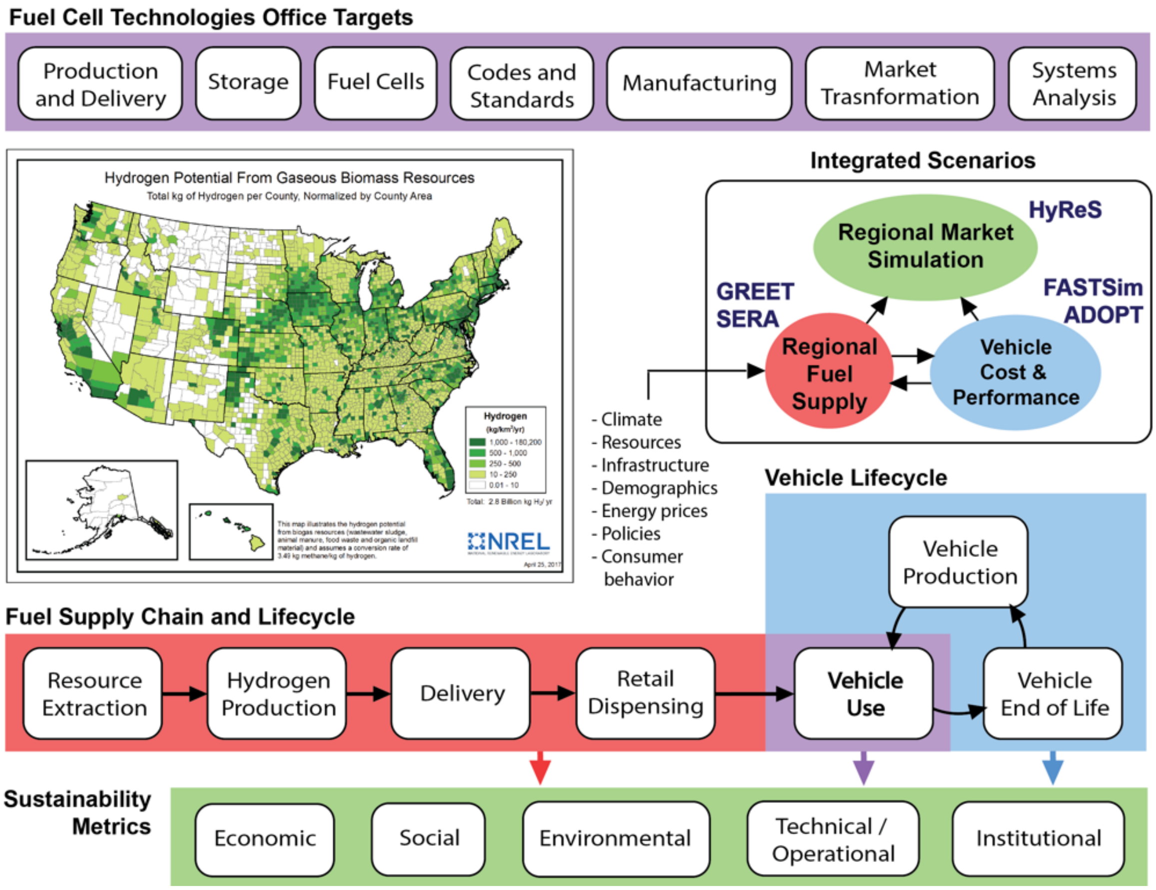


**FIGURE 1.** HyReS framework scope and sustainability metrics with respect to FCTO targets, fuel and vehicle life cycle stages, and regional integrated market assessment

to the natural gas pathways, the renewable-based pathways result in a 55–75% reduction in life cycle GHG emissions. On the other hand, the "GH2 from Poplar via Pipeline" pathway results in the highest life cycle water usage, where over 50% of the life cycle water usage is associated with the production of the poplar biomass.

Because the "LH2 from NG via Truck" pathway requires the most electricity, its life cycle GHG emissions are the most sensitive to the regional electricity mix. The baseline well-to-pump GHG emissions (based on the U.S. average grid mix) increase by up to 36% for this pathway. The grid mix associated with West Virginia has the highest GHG intensity due to the relatively high proportion of electricity from coal. In West Virginia, for example, results show that the FCEVs based on the "LH2 from NG via Truck" pathway produce up to 25% more life cycle GHG emissions than gasoline vehicles on a per-mile basis.

The baseline GHG results, shown in Figure 3, reveal that all four hydrogen supply pathways result in FCEVs with lower life cycle GHG emissions per mile than conventional gasoline vehicles. We compare these pathways also to HEVs and find that all but the "LH2 from NG via Truck" are less GHG-intensive. When comparing the "GH2 from Poplar via Pipeline" FCEV to a vehicle running on ethanol produced from poplar, results show that the FCEV produces 50% more GHG emissions over the life cycle. This difference is mostly due to the co-production of electricity during ethanol production, the displacement of which results in GHG credits for the ethanol life cycle. The default GREET assumptions include electricity co-generation for ethanol production, while the default biomass-to-hydrogen pathway does not include co-generation. The FCEV based on hydrogen from wind electrolysis is compared to an electric vehicle powered by wind with a range of 400 miles. In order to make such a comparison, it was necessary to simulate vehicle specifications for the battery electric vehicle (BEV400) and then make modifications to the GREET model accordingly. The results show that the BEV400 from wind has lower life cycle GHG emissions than the "GH2 from Wind via Pipeline" FCEV, because the electricity for transportation and distribution is assumed as the U.S. average grid mix as opposed to 100% renewable. Recent research [8,9] suggests that the GHG emissions of battery materials and manufacturing may actually be up to an order of magnitude higher than the GREET results. Figure 3 includes a symbol

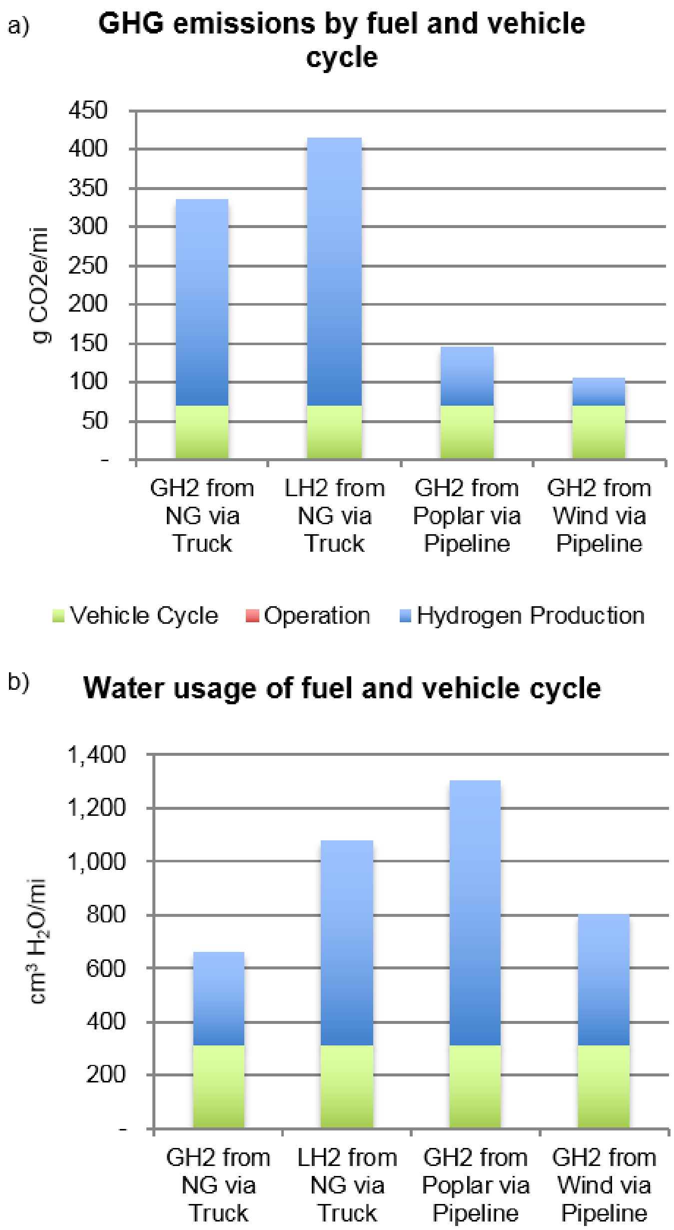


**FIGURE 2.** Life cycle (a) GHG emissions and (b) water usage associated with four hydrogen supply pathways for FCEVs

representing the life cycle emissions of a BEV400 (with electricity generated from wind) that uses the battery production cycle emissions from [9] in addition to the other GREET-based life cycle emissions. When the additional emissions from battery materials and manufacturing are taken into account, the FCEV from wind appears to be less GHG-intensive. These results will be revised according to future GREET model updates.

While the results presented in this report are limited to GHG emissions and water usage, other metrics from the GREET model are being integrated into the HyReS framework, such as petroleum and other fossil fuel consumption and criteria air pollution emissions. The HyReS framework is spatially and temporally explicit in assessing environmental impacts, allowing for location-based benefits to be calculated and monetized. For example, the COBRA model [4] can be used to monetize the costs and benefits associated with increases or decreases in local and regional criteria pollution emissions.

The social cost of GHGs [10], air pollution benefits from the COBRA model, energy security benefits [11], and water reduction benefits [12] are assessed as part of the HyReS framework. Figure 4 indicates the monetized benefit results for the four case study pathways in terms of dollars per one million conventional vehicle gasoline miles displaced. The baseline impacts (on a national scale) from each pathway are used for calculating these monetized benefits presented. The results show that the “GH2 from Wind via Pipeline” pathway accrues the highest benefits from displacing one million gasoline miles, with the highest level of benefits corresponding to reductions in criteria pollutant emissions.

## CONCLUSIONS AND FUTURE WORK

The results from analyzing the environmental impacts of four hydrogen supply pathways reveal that FCEVs tend to have lower life cycle GHG emissions than conventional gasoline vehicles, in addition to lower criteria emissions, petroleum use, and water use. Monetizing the social benefits of these reductions results in up to $60,000 worth of benefits (from the “GH2 from Wind via Pipeline” pathway) associated with displacing one million gasoline miles. However, calculating results using state-based electricity mixes emphasizes the importance of spatially explicit analyses, with electricity mix being a major factor in determining whether FCEVs perform better or worse than conventional vehicles (i.e., result in a net positive or negative social benefit on a life cycle basis).

Future work includes expanding the framework beyond the case studies to incorporate analytic representations of all metrics associated with major hydrogen supply pathways and ensuring that regional hydrogen supply pathways are made consistent with the benchmark fuel pathways. Second, the framework will be applied to major supply chain components in a manner that allows for both project-specific evaluations (e.g., a particular hydrogen production facility or transmission pipeline) as well as general high-level assessments of geographically extensive supply networks (e.g., networked supply chains serving multiple demand centers in the Midwest). Third, additional work will ensure that HyReS is in alignment with goals and metrics in use by representative companies, government agencies, and other relevant stakeholders.

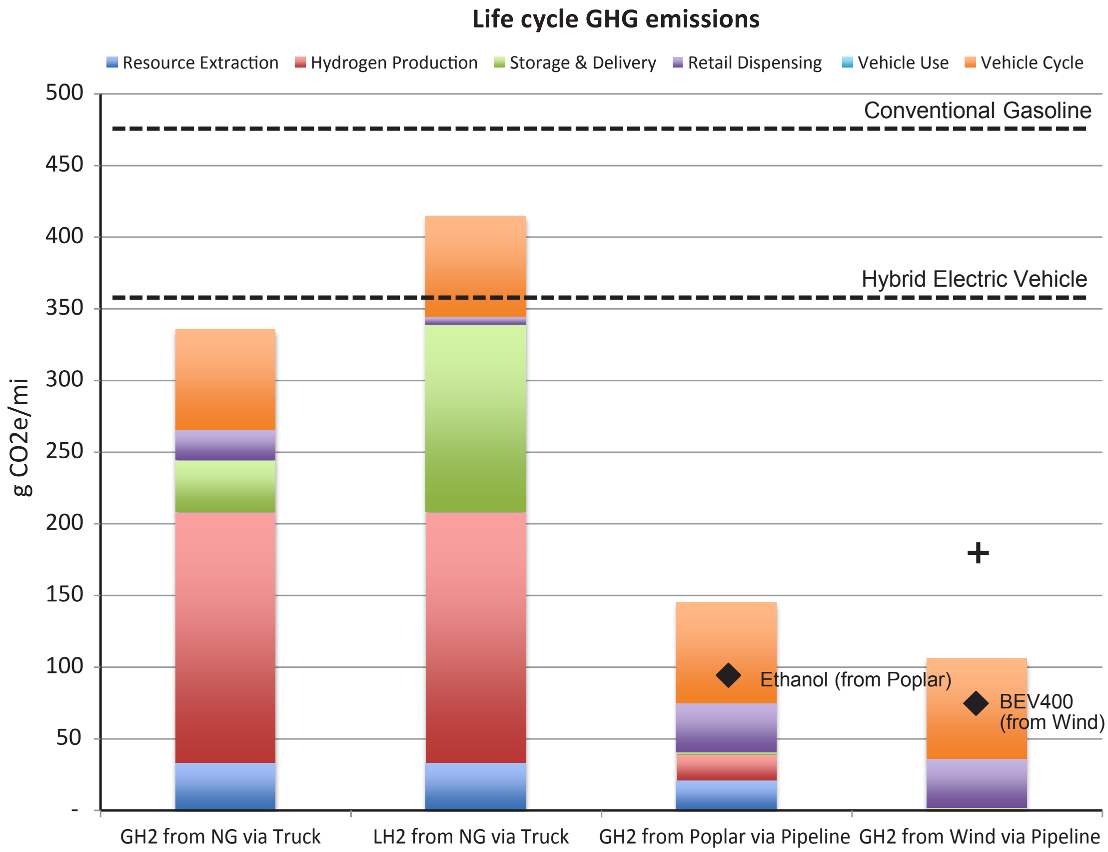


**FIGURE 3.** Baseline life cycle GHG-100 emissions per mile by stage of each hydrogen FCEV case study pathway, benchmarked against four reference vehicle–fuel systems: conventional gasoline vehicle, HEV, ethanol (from poplar) vehicle, and BEV400 from wind. The + represents the life cycle GHG emissions of a BEV400 using the per-kWh emissions from Kim et al. (2016).

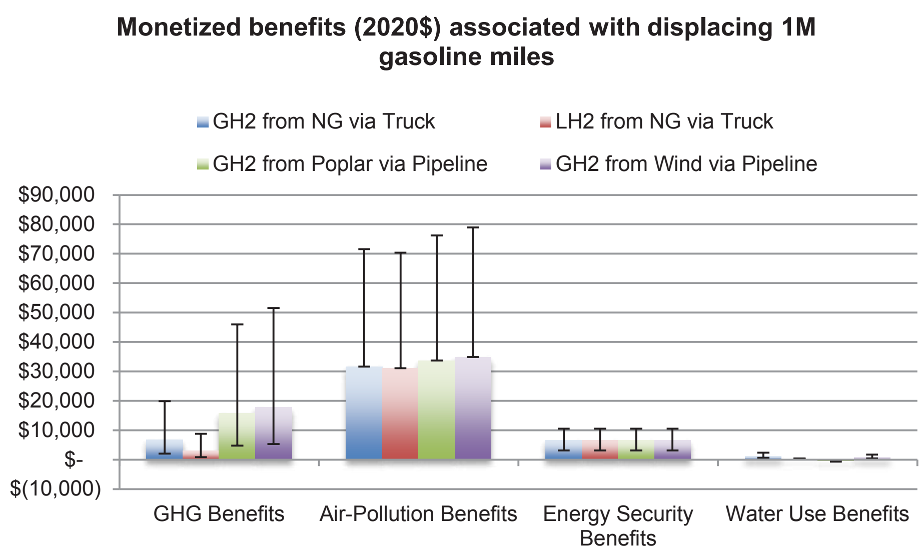


**FIGURE 4.** Monetized benefits associated with displacing one million gasoline miles with an FCEV fueled by one of the four hydrogen supply pathways

## FY 2017 PUBLICATIONS/PRESENTATIONS

**1.** Connelly, E., Melaina, M., Lambert, J., and Linkov, I., "Resilience Analysis to Inform Priority-Setting." Presentation. Society for Risk Analysis Annual Meeting, San Diego, CA, December 11–15, 2016.

**2.** Connelly, E., Melaina, M., "Strategic Analysis of Transportation Policies." Poster Presentation. NREL Postdoc Career and Networking Fair, Golden, CO, February 23, 2017.

**3.** Connelly, E., Melaina, M., "Incorporating Resilience into Transportation Infrastructure Planning." Presentation. 2017 Joint Conference International Society for Industrial Ecology and International Symposium on Sustainable Systems and Technology, Chicago, IL, June 25–29, 2017.

**4.** Melaina, M., Connelly, E., Chen, Y., "Sustainability Analysis: Hydrogen Regional Sustainability (HyReS)." Presentation at the 2017 Annual Merit Review and Peer Evaluation Meeting, June 6, 2017, Washington, DC. Available from https://www.hydrogen.energy.gov/pdfs/review17/sa059_melaina_2017_o.pdf

**5.** Connelly, E., Melaina, M., Chen, Y., and Sperling, J., *Hydrogen Regional Sustainability (HyReS): Analytic Framework and Case Study Results.* Prepared for the U.S. Department of Energy's Fuel Cell Technologies Office. 2017. *Forthcoming.*

## REFERENCES


**1.** Melaina, M. "SERA Scenarios of Early Market Fuel Cell Electric Vehicle Introductions: Modeling Framework, Regional Markets, and Station Clustering." NREL/PR-5400-64395. Presented at the 2015 ICEPAG Conference, Irvine, CA, March 23, 2015. Available online: http://www.nrel.gov/docs/fy15osti/64395.pdf

**2.** Bush, B., Melaina, M., Penev, M., Daniel, W., "SERA Scenarios of Early Market Fuel Cell Electric Vehicle Introductions," National Renewable Energy Laboratory, Technical Report NREL/TP-5400-56588, 2013. Available from http://www.nrel.gov/docs/fy13osti/56588.pdf

**3.** EPA. *Environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE).* U.S. Environmental Protection Agency, 2016. Available online: https://www.epa.gov/benmap

**4.** EPA. *Co-Benefits Risk Assessment (COBRA) Screening Model*. U.S. Environmental Protection Agency, 2015. Available online: https://www.epa.gov/statelocalclimate/co-benefits-risk-assessment-cobra-screening-model

**5.** Elgowainy, A., Dieffenthaler, D., Sokolov, V., Sabbisetti, R., Cooney, C., and Anjum, A. *The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model (v1.3.0.13081).* [Software]. Argonne National Laboratory. 2013. Available from https://greet.es.anl.gov/

**6.** Brooker, A., Gonder, J., Lopp, S., and Ward, J., "ADOPT: A Historically Validated Light Duty Vehicle Consumer Choice Model," SAE Technical Paper 2015-01-0974. 2015. doi:10.4271/2015-01-0974.

**7.** Brooker, A., Gonder, J., Wang, L., Wood, E. et al., "FASTSim: A Model to Estimate Vehicle Efficiency, Cost and Performance," SAE Technical Paper 2015-01-0973. 2015. doi:10.4271/2015-01-0973.

**8.** Ellingsen, L.A.-W., Majeau-Bettez, G., Singh, B., Srivastava, A.K., Valøen, L.O., and Strømman, A.H. "Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack." *Journal of Industrial Ecology,* 18: 113–124. 2014. doi:10.1111/jiec.12072

**9.** Kim, H.C., Wallington, T.J., Arsenault, R., Bae, C., Ahn, S., and Lee, J. "Cradle-to-gate emissions from a commercial electric vehicle Li-ion battery: a comparative analysis." *Environmental science & technology*, 50(14), 7715–7722. 2016.

**10.** U.S. Government Interagency Working Group on Social Cost of Greenhouse Gases. "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866." 2016. Available online: https://www.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf

**11.** EPA and NHTSA. "Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule." 2010. Available online: https://www.gpo.gov/fdsys/pkg/FR-2010-05-07/pdf/2010-8159.pdf

**12.** Ecolab and Trucost. *Water Risk Monetizer* [Software]. 2015. Available from https://www.waterriskmonetizer.com/