# H2@Scale Analysis

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## Overall Objectives

- Improve fidelity of the value proposition of H2@Scale.
- Provide results that are supported by in-depth analysis of market potential and economics.
- Quantify potential impacts on economics, resource use, and emissions metrics.
- Identify regional opportunities and challenges.

## Fiscal Year (FY) 2018 Objectives

- Incorporate feedback on the technical potential of hydrogen production in the United States via diverse approaches, and on the maximum market size for potential hydrogen demands.
- Develop national supply curves for hydrogen, assuming diverse methods of hydrogen production, and national demand curves for hydrogen consumption in current and potential future applications.
- Quantify the national economic potential of H2@Scale under several scenarios
- Complete a draft report summarizing the technical and economic potential of the H2@Scale concept.

## Technical Barriers

This project addresses the following technical barriers from the Systems Analysis section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration (MYRDD) Plan[1]:

(A) Future Market Behavior—Potential market for low-value energy and potential hydrogen markets beyond transportation

(D) Insufficient Suite of Models and Tools—Tools integrating hydrogen as an energy carrier into the overall energy system and quantifying the value hydrogen provides

(E) Unplanned Studies and Analysis—H2@Scale is a new concept and requires analysis of its potential impacts for input in prioritizing research and development.

It also addresses the following technical barriers from the Technology Validation section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

(F) Centralized Hydrogen Production from Fossil Resources—Investigating potential value stacks for hydrogen production from various resources

(G) Hydrogen Production from Renewable Resources—Investigating the potential for hydrogen to be produced from renewable electricity and support higher penetrations of renewable electricity generation.

## Contribution to Achievement of DOE Milestones

This project will contribute to achievement of the following DOE milestone from the Systems Analysis section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

[1] https://www.energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

- 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).

In addition, this project will contribute to achievement of the following DOE milestone from the Technology Validation section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

- Milestone 3.9: Validate large-scale system for grid energy storage that integrates renewable hydrogen generation and storage with fuel cell power generation by operating for more than 10,000 hours with a round-trip efficiency of 40% (4Q, 2020).

## FY 2018 Accomplishments

- Updated the estimate of the current maximum hydrogen demand market size to be 151 million metric tonnes (MMT) annually, including demands from refineries and the chemical processing industry, metals refining, ammonia production, hydrogen use for biofuels refining, hydrogen use for synthetic fuels production, direct injection into the nation's natural gas system, light-duty fuel cell electric vehicles (FCEVs), other transportation including medium-duty and heavy-duty trucks, and seasonal energy storage for the electricity grid.
- Developed four national supply curves for hydrogen consisting of supplies from steam reforming of natural gas, high-temperature electrolysis using nuclear energy, and low-temperature electrolysis of otherwise curtailed electricity. The scenarios vary based on varying assumptions of natural gas prices, low-temperature electrolyzer prices, and electricity market structures.
- Developed three national demand curves for the hydrogen demands listed in a previous bullet. The curves vary depending upon assumptions regarding the evolution of the U.S. electricity system and the U.S. metals industry.
- Quantified the national economic potential for H2@Scale ranging from 22 MMT/yr to 45 MMT/yr over five scenarios with various technology and market assumptions.

## INTRODUCTION

H2@Scale is a U.S. Department of Energy (DOE) initiative that brings together stakeholders to advance affordable hydrogen production, transport, storage, and utilization to increase revenue opportunities in multiple energy sectors. The focus of this report is techno-economic modeling and analysis that was completed to characterize the overall potential of the H2@Scale vision, given evolutions in the U.S. energy system and future R&D advances. Figure 1 graphically represents H2@Scale by showing how hydrogen could fit into the overall energy system. It is based on utilizing hydrogen's unique ability to both support the electric grid and serve as a clean feedstock to a variety of demands. Hydrogen production can utilize intermittent electricity and heat, and therefore it can be used to stabilize the electricity grid and to enhance the financial viability of both baseload nuclear power and variable renewable generation. The hydrogen that is produced in that way can be stored for months without degradation and then used to provide electricity back to the grid or for a number of alternative purposes shown in Figure 1, including as fuel for FCEVs, as a chemical feedstock for refining and ammonia production, and as a clean energy supplement in the natural gas system.

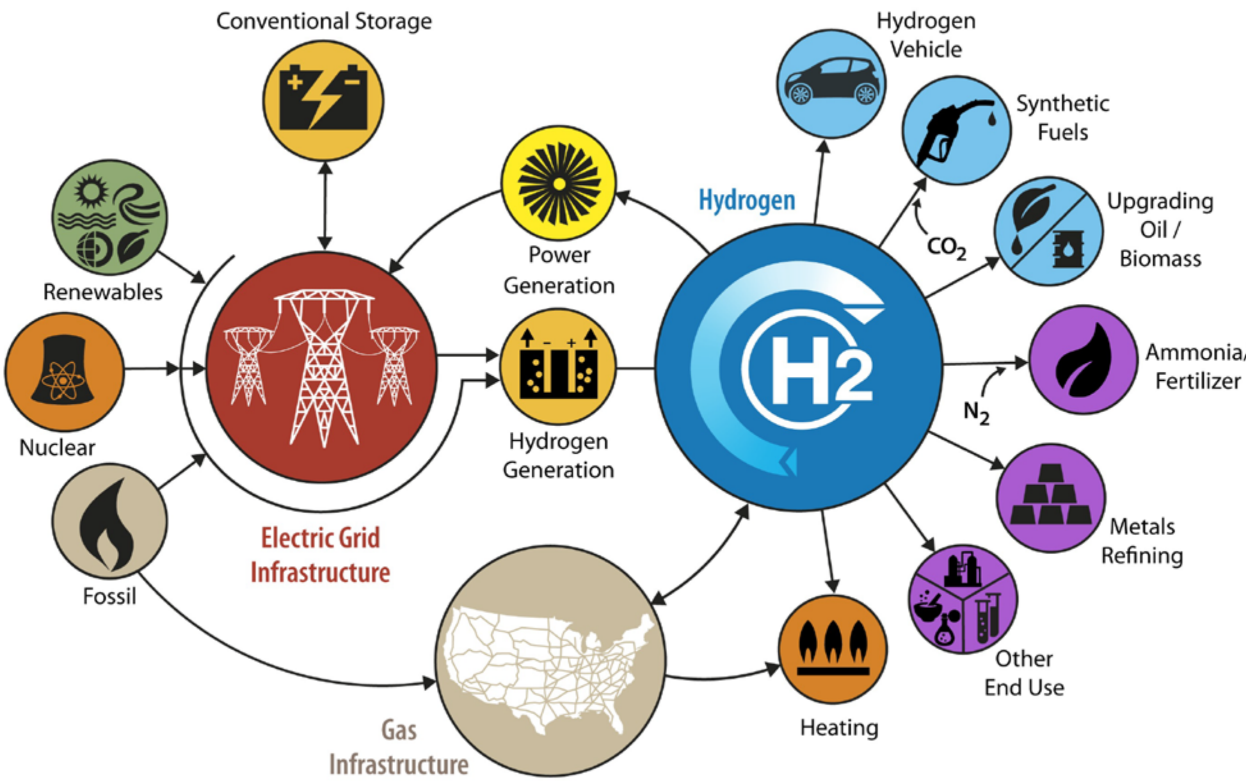


Figure 1. Graphical depiction of the H2@Scale concept, showing the use of otherwise curtailed electricity and other hydrogen generation resources and potential uses of hydrogen, including on-demand electricity, transportation, and industrial uses, in addition to injection into the natural gas infrastructure.

This project analyzes the economic potential of H2@Scale. It focuses on developing and communicating potential market size and impacts using techniques that can be justified and communicated to a broad range of audiences. Preliminary regional analyses and transition conceptualization are being performed in this project. Proposed work in future years extends the analysis to consider regional issues in depth, as well as storage and infrastructure development opportunities and challenges.

## APPROACH

This project is composed of three stages. The first two are estimating (1) the maximum hydrogen market size under the H2@Scale concept and (2) the economic potential of the H2@Scale concept; these stages were initiated in FY 2017 and completed in FY 2018—excepting finalizing publications. The third stage, including additional analysis related to topics such as regional needs and constraints and storage and infrastructure development opportunities and challenges, has been initiated but will not be reported here.

The team estimated the economic potential as the market equilibrium between supply and demand using traditional micro-economic analysis techniques based on a theory of competitive markets, in which the price of a particular good will settle at a point where the quantity demanded at that price matches the quantity supplied at that price [1–2]. Demand curves were developed by estimating hydrogen price points based on users' willingness to pay for hydrogen (which is impacted by alternatives and elasticity), and potential locations for the following potential hydrogen demands: oil refining, metals refining, ammonia, biofuels, synthetic fuels and chemicals, supplementing natural gas, light-duty vehicles, other transportation, and seasonal energy storage for the electrical grid. Supply curves for hydrogen production via steam reforming of natural gas, low-temperature electrolysis of otherwise curtailed electricity, and high-temperature electrolysis using heat from nuclear energy were developed based on energy resource and technology cost assumptions including those from [3–5].

## RESULTS

The maximum market sizes for hydrogen demand in the United States is estimated as 151 MMT/yr. This demand estimate comprises 74 MMT/yr for use in FCEVs, 28 MMT/yr for seasonal storage to ultimately be used in electricity generation, and 49 MMT/yr for industrial use (including oil refining and the chemical processing industry, metals, ammonia, biofuels, and synthetic fuels and chemicals) and blending into the natural gas system. Table 1 summarizes the maximum market sizes for hydrogen demands. The technical potential of U.S. resources is sufficient to supply the maximum potential hydrogen market.

Table 1. Maximum Market Size for Hydrogen Demands

| Application | Maximum Market Size (MMT/yr) |
|---|---|
| Refineries and the chemical processing industry[a] | 8 |
| Metals | 12 |
| Ammonia | 4 |
| Biofuels | 1 |
| Synthetic fuels and chemicals | 14 |
| Natural gas supplementation | 10 |
| Light-duty FCEVs | 57 |
| Other transportation | 17 |
| Seasonal energy storage for the electricity grid | 28 |
| Total | 151 |

[a] Chemical processing industry not including metals, ammonia, methanol, or biofuels.

The team developed aggregated demand curves by combining demand quantities across the range of price points that the user is estimated to be willing to pay for hydrogen. The aggregated demand curves for each scenario are shown in Figure 2. The Business As Usual and Low NG (natural gas) Resource scenarios have the same demand curves above a hydrogen price of $1.48/kg. Below this price point, deviations in these scenarios are due to differences in assumed natural gas prices, which influence hydrogen's viability in seasonal energy storage. The Increased Metals Refining, Improved Electrolysis, and Low Cost Electrolysis scenarios all assume the same demand curve, which is 4 MMT greater than in the Low NG Resource scenario at prices above $1.70/kg and below $2.50/kg; this additional demand is expected to come from the metals refining sector. Competition between industries that use hydrogen (e.g., demand for hydrogen in gasoline production for use in internal combustion engine vehicles vs. demand for hydrogen for use in FCEVs) was assumed to have no significant effect on the cumulative market sizes. Such secondary effects were outside of the scope of this analysis. For example, the independent demand for refining is 7.5 MMT/yr, and the independent demand for light-duty vehicles is 23.7 MMT/yr. In scenarios with the hydrogen price low enough to include both demands, we estimate the quantity of hydrogen to be the sum of the refining and light-duty vehicle demands (31.2 MMT/yr) because excess refining products could be exported; that market analysis is outside the scope of this effort.

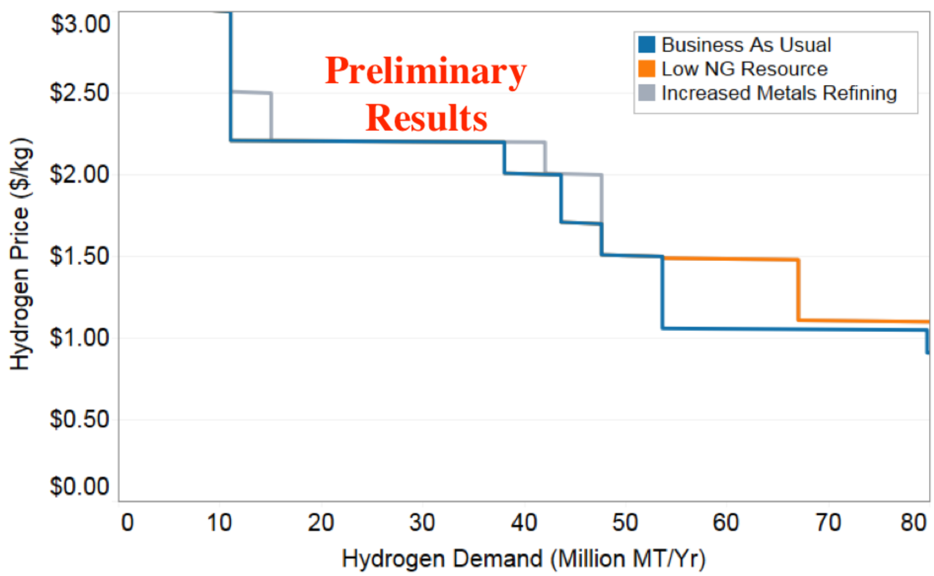


Figure 2. Aggregated demand curves for H2@Scale scenarios

The team estimated national supply curves based on production cost estimates for natural gas reforming, high-temperature electrolysis of nuclear energy, and low-temperature electrolysis of otherwise curtailed electricity, along with assumptions of the cost of delivery. The cost of hydrogen delivery can vary widely, given the proximity of production to demand. In the current work, simple assumptions of delivery cost have been made. The cost of infrastructure will be expanded in analysis in the coming years. Figure 3 shows the supply curves used in the analysis.

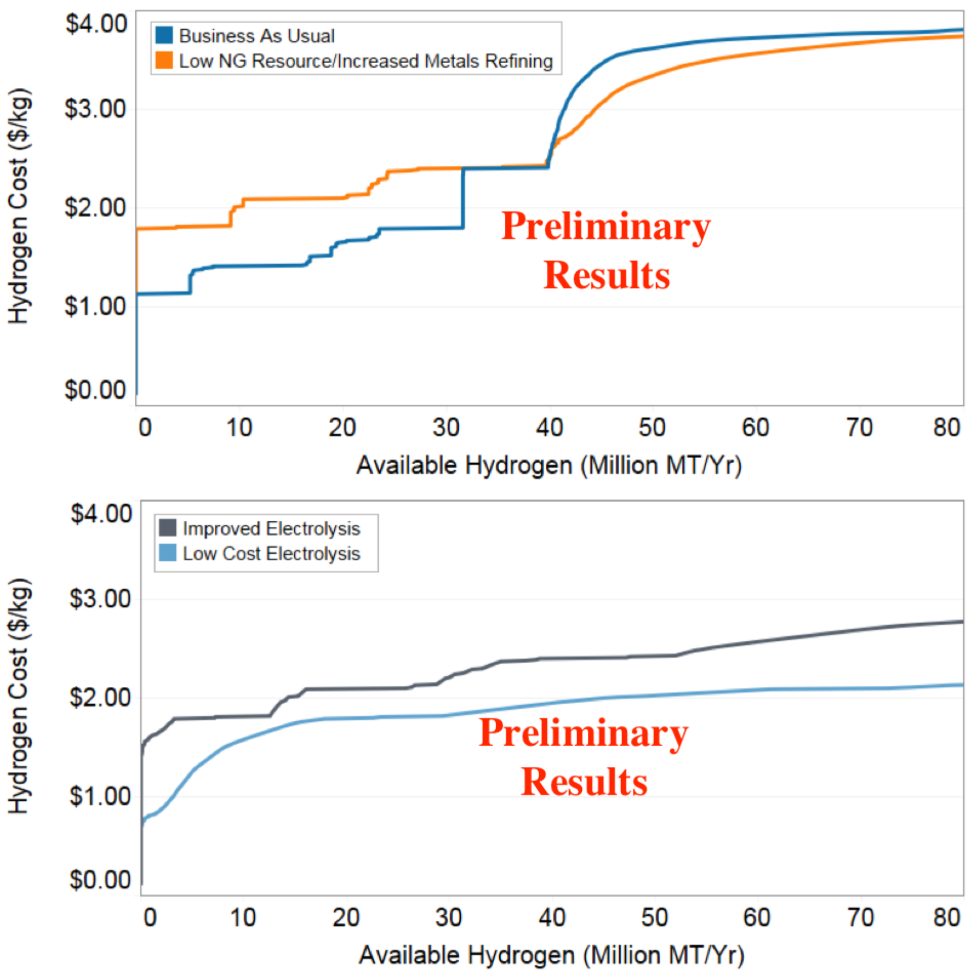


Figure 3. Aggregated supply curves for H2@Scale scenarios

The team estimated the economic potential of H2@Scale at the intersection between national supply and demand curves for five scenarios. The scenarios include varying assumptions about future conditions, including the performance of related markets (e.g., natural gas prices), the potential for market accessibility (e.g., the opportunity to purchase otherwise curtailed electricity at the selling price into the wholesale market), and other national decisions (e.g., whether a premium will be paid for domestically produced metals). Figure 4 shows the supply and demand curves of each scenario. The results range from 22 to 45 MMT/yr hydrogen market sizes. Across all the scenarios, hydrogen is demanded for refineries and the chemical processing industry, ammonia production, biofuels production, light-duty vehicles, and other transport; however, the quantities for light-duty vehicles and other transport vary. Some scenarios indicate a potential hydrogen demand for metals refining and methanol production.

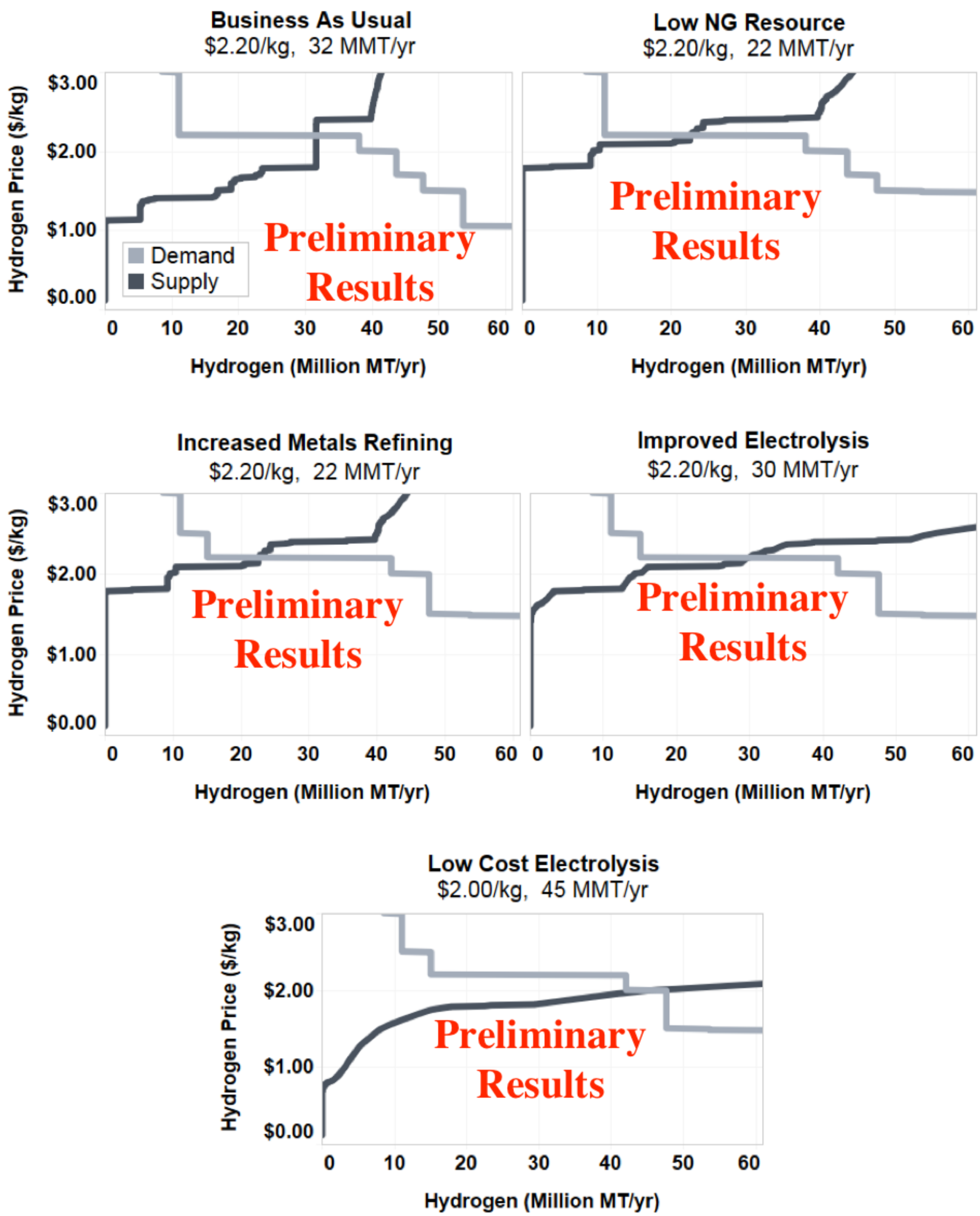


Figure 4. Supply and demand curves for the economic potential of five H2@Scale scenarios. Results are in the process of being finalized.

## CONCLUSIONS AND UPCOMING ACTIVITIES

The team's analysis indicates that the H2@Scale concept could have a large impact on the U.S. energy system. At 151 MMT/yr, the maximum potential hydrogen market is approximately 15 times larger than the current market. Most of that potential demand would be for applications that hydrogen is not currently supporting, and all of it is not likely to be achieved economically. The team estimated the economic potential of hydrogen in the United States to be 22–45 MMT/yr, depending on resource prices, hydrogen production technology R&D, and the price various users will pay for hydrogen, which depends in part on the cost of other technologies that provide the same services. These estimates are based on markets reaching equilibrium.

The team attempted to consider the full spectrum of hydrogen demands and most production options, but others should be considered as they are identified. Additional supply options including biomass and biogas conversion have not been included in the analysis to date. While these feedstocks already have other markets, an understanding of the competition between these markets would improve estimates of hydrogen supply potential. Delivery costs estimated in this analysis were simple assumptions. In-depth estimates of the necessary delivery and storage infrastructure would improve characterization of hydrogen supply potential. Finally, the estimates described here are based on markets achieving equilibrium. Market development and transition studies would improve understanding of challenges in achieving these penetrations.

## FY 2018 PUBLICATIONS/PRESENTATIONS

1. Mark Ruth, Paige Jadun, and Amgad Elgowainy, "Potential Size of and Value Proposition for H2@Scale Concept" (presentation at the American Institute of Chemical Engineers Annual Meeting, November 1, 2017).
2. Mark Ruth, Paige Jadun, and Bryan Pivovar, "H2@Scale: Technical and Economic Potential of Hydrogen as an Energy Intermediate" (presentation at the Fuel Cell Seminar, November 9, 2017).
3. Mark Ruth and Paige Jadun, "H2@Scale Analysis and Project Developments" (presentation to the Hydrogen Technical Advisory Committee, February 13, 2018).
4. Mark Ruth, Paige Jadun, and Amgad Elgowainy, "H2@Scale Analysis" (presentation at the 2018 Fuel Cell Technologies Office Annual Merit Review, June 13, 2018).
5. Mark Ruth, "H2@Scale Value Proposition Considerations" (presentation at the H2@Scale R&D Consortium Kickoff Meeting, August 1, 2018).

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