U.S. DEPARTMENT OF ENERGY

Response to Findings and Recommendations of the Hydrogen and Fuel Cell Technical Advisory Committee during Fiscal Years 2014 and 2015

Fifth Biennial Report to Congress
October 2016

United States Department of Energy
Washington, DC 20585

Message from the Secretary

This is the Department of Energy's fifth biennial report to Congress, provided in response to the Energy Policy Act of 2005 ("EPACT 2005").[1] EPACT 2005 established the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) to advise the Department of Energy on programs and activities under EPACT 2005 Title VIII, *Hydrogen*.

EPACT 2005 states that HTAC is to review and make recommendations to the Secretary on:

1. The implementation of programs and activities under Title VIII of EPACT 2005;
2. The safety, economical, and environmental consequences of technologies for the production, distribution, delivery, storage or use of hydrogen energy and fuel cells; and,
3. The plan called for by section 804 of EPACT 2005, known as the *DOE Hydrogen and Fuel Cells Program Plan* (formerly the *Hydrogen Posture Plan*).

Section 807 also requires the Department of Energy to transmit a biennial report to Congress that responds to recommendations made by HTAC since the previous report. This document, *Response to Findings and Recommendations of the Hydrogen and Fuel Cell Technical Advisory Committee: Fifth Biennial Report to Congress*, is the Department of Energy's official response to recommendations made by HTAC during fiscal years 2014 and 2015.

This report is being provided to the following Members of Congress:

- **The Honorable Fred Upton**
  Chairman, House Committee on Energy and Commerce
- **The Honorable Frank Pallone, Jr.**
  Ranking Member, House Committee on Energy and Commerce
- **The Honorable Lisa Murkowski**
  Chairman, Senate Committee on Energy and Natural Resources
- **The Honorable Maria Cantwell**
  Ranking Member, Senate Committee on Energy and Natural Resources

If you have any questions or need additional information, please contact me or Brad Crowell, Assistant Secretary for Congressional and Intergovernmental Affairs, at (202) 586-5450.

Sincerely,

Ernest J. Moniz

---

[1] Specifically, section 807(d)(2) of the Energy Policy Act of 2005, P.L. 109-58, August 8, 2005.

Executive Summary

The body of this report consists of 13 recommendations made by HTAC since the previous biennial report. These recommendations were delivered through a summary report from the HTAC Hydrogen Enabling Renewables Working Group (October 2013), a letter on the state of hydrogen infrastructure (November 2013), and two annual state-of-the-industry reports, in June 2014 and May 2015. These documents are provided in the appendices to this report.

In the "Hydrogen Enabling Renewables Working Group Summary Report," HTAC stated that assessing the economic viability of hydrogen production as a renewable energy storage pathway should be a high priority for the Department of Energy (DOE) and the renewable/electric industry, working in partnership. Recommendations included assessing energy storage for wind integration, community energy for load leveling and vehicle fueling, and potential applications for power-to-gas energy storage systems. Recommendations also included determining if there are national policies being considered that would significantly increase renewable penetration and conducting sensitivity analyses, including and excluding policy scenarios.

HTAC's Letter on Hydrogen Infrastructure recommended that the Department show "emphatic public support" for fuel cell electric vehicle deployment. It encouraged collaboration with international infrastructure initiatives, as well as direct investment with states and industry. This letter also noted reductions in the Department's budget for hydrogen and fuel cell research in recent years.

The primary theme of HTAC's cover letter accompanying its 2013 Annual Report also focused on the need for increased funding levels for hydrogen and fuel cells research. The most recent recommendations to the Department from the cover letter to the 2014 HTAC Annual Report highlighted the importance of the alternative fuel vehicles tax incentive and reiterated the importance of funding for the U.S. to remain globally competitive. The Department addressed both of these recommendations in FY2014-FY2016.

This report presents these recommendations based on the source material (see Appendices), followed by DOE's responses. The report also includes a description of how the Secretary has implemented or plans to implement HTAC's recommendations or an explanation of the reasons that a recommendation will not be implemented.

It should be noted that a major deliverable by the Department in 2015 was the Quadrennial Technology Review (QTR). The QTR examines research, development, demonstration, and deployment opportunities across energy technologies to effectively address the Nation's energy needs. The QTR includes discussion of hydrogen and fuel cell technologies in multiple chapters as well as in the appendices.[2]

[2] Quadrennial Technology Review, 2015, http://energy.gov/quadrennial-technology-review-2015.

RESPONSE TO FINDINGS AND RECOMMENDATIONS OF THE HYDROGEN AND FUEL CELL TECHNICAL ADVISORY COMMITTEE DURING FISCAL YEARS 2014 AND 2015

Table of Contents

I. Legislative Language

The Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) was established under the Energy Policy Act of 2005 ("EPACT 2005"), P.L. 109-58, August 8, 2005, to advise the Secretary on programs and activities under EPACT 2005 Title VIII, Hydrogen. Section 807 requires HTAC to review and make recommendations to the Secretary on:

1. The implementation of programs and activities under Title VIII of EPACT 2005;
2. The safety, economic, and environmental consequences of technologies for the production, distribution, delivery, storage, or use of hydrogen energy and fuel cells; and,
3. The plan called for by section 804 of EPACT, also known as the *DOE Hydrogen and Fuel Cells Program Plan* (*Program Plan*, formerly the *Hydrogen Posture Plan*).

In this report, DOE is responding to section 807(d)(2) of EPACT 2005, which requires that:

> *The Secretary shall transmit a biennial report to Congress describing any recommendations made by the Technical Advisory Committee since the previous report. The report shall include a description of how the Secretary has implemented or plans to implement the recommendations, or an explanation of the reasons that a recommendation will not be implemented.*

II. Recommendations from Hydrogen Enabling Renewables Working Group Summary Report

The Hydrogen Enabling Renewables Working Group was established by HTAC to identify ways in which hydrogen might serve as an "enabler" for high penetration of renewable energy technologies in the United States. In December 2013, HTAC submitted a subcommittee report to the Department detailing two models for evaluating hydrogen energy storage against other competing storage technologies. This report was accompanied by the following specific recommendations.

Recommendations

> ***Energy Storage for Wind Integration:*** *Determine if there are national policies being considered that would significantly increase renewable penetrations as a means to reduce greenhouse gas emissions. Conduct system analyses including and excluding long-term storage using policy scenarios identified, and from these analyses, estimate the value of hydrogen energy storage to the overall system under those scenarios. Determine what value the government could assign to otherwise curtailed renewables to make multi-day/week scale hydrogen (and other) energy storage economical.*
>
> ***Community Energy for Load Leveling and Vehicle Fueling:*** *Conduct sensitivity analyses to determine what conditions are necessary for a hydrogen system to compete with electric battery system for fueling FCV and EV vehicles, respectively, with solar PV energy. Determine the community scale at which hydrogen storage competes with battery storage for solar PV load leveling and vehicle fueling.*
>
> ***Other:*** *Consider investigating potential U.S. applications for "power-to-gas" energy storage systems and, if deemed to have potential, initiate a dynamic economic study (supported by the relevant teams at DOE, the national laboratories) to evaluate the system wide and integrative benefits of such hydrogen storage system for U.S. markets."*

Response

The Department recognizes that increasing penetration of renewable technologies is a key feature in both the recommendations of the Working Group and in national policies. Renewables feature strongly in President Obama's Climate Action Plan (CAP). CAP's first of three pillars, "Cutting Carbon Pollution in America," presents "Promoting American Leadership in Renewable Energy" as a key solution pathway. During the Obama administration, the United States has seen major strides in deploying clean energy and reducing their costs. Over the last six years, costs have fallen by 40 to 90 percent for technologies such as wind energy, solar, batteries, and LED lighting, and deployment has increased. Wind generation capacity has tripled, solar has increased 20-fold, and LEDs 200-fold over the same time period.[3]

The Department continues to conduct systems analysis under different scenarios to determine economic and technical benefits of various approaches, including the examples provided in the above HTAC recommendations. In addition, in May 2014, the Department's Fuel Cell Technologies Office partnered with Industry Canada to hold a workshop on Hydrogen Energy Storage for Grid and Transportation Services to address several HTAC recommendations. The international experts at the workshop identified challenges, benefits, and opportunities for commercial hydrogen energy storage applications to support grid services, variable electricity generation, and hydrogen vehicles.[4] Another workshop focused on more detailed scenarios is planned for late 2016 and will be included in the 2016-2017 biennial report.

More specifically, the Department's Fuel Cell Technologies Office provided about $6 million total for fiscal years 2014 and 2015 on national laboratory-led efforts to (1) assess the viability of hydrogen energy storage, and (2) experimentally demonstrate the technical viability of specific approaches and technology components. In addition, the Department has invested more than $135 million to establish a state-of-the-art Energy Systems Integration Facility at the National Renewable Energy Laboratory (NREL) to focus on research, development, and demonstration of integrated energy systems. The facility has unique capabilities to overcome challenges related to integration of renewable energy technologies into the electricity grid and to advance energy storage technologies, including hydrogen.

In 2015, the Department initiated a study in collaboration with the California Air Resources Board (CARB) to evaluate hydrogen generation as a means to avoid curtailing renewables as well as serve as a fuel and feedstock for other applications. The results of this study will be available by late 2016 and will be shared with the Committee.

Finally, the Department initiated a $1.4 million project through NREL, along with key industry partners, to demonstrate the power-to-gas approach by producing hydrogen via electrolysis and blending the hydrogen with natural gas, thereby reducing greenhouse gas emissions and avoiding the curtailment of renewables. The objectives of this project were previously presented to HTAC and future updates are planned once the demonstration is complete.

---

[3] U.S. Energy Secretary Ernest Moniz Statement on Conclusion of COP21 Climate Negotiations, December 2013, http://energy.gov/articles/us-energy-secretary-ernest-moniz-statement-conclusion-cop21-climate-negotiations.

[4] http://energy.gov/eere/fuelcells/downloads/hydrogen-energy-storage-grid-and-transportation-services-workshop.

III. Recommendations from Hydrogen Infrastructure Letter

In November 2013, HTAC submitted a letter to the Secretary identifying six recommendations for the Department to use as guidelines for enabling the growth of hydrogen infrastructure. This letter also contained nine points illustrating the status of hydrogen infrastructure in the U.S.

Recommendation

> *"Emphatic public support by the U.S. government for fuel cell electric vehicle (FCEV) deployment will give public and private stakeholders confidence and increase public awareness at a critical point in the commercialization cycle."*

Response

The Department agrees that public support of hydrogen and fuel cells has significant impact on public and private stakeholder confidence. During the two years covered by this report, the Fuel Cell Technologies Office published nearly 200 news items including blogs, news articles and social media items (Facebook posts, etc.) to increase public visibility of hydrogen and fuel cell technologies. These include not only FCEVs but early markets such as the Department's project demonstrating the world's first fleet of hydrogen fuel cell airport ground support equipment in Memphis.

The Office's monthly newsletter reaches more than 12,000 readers. Various officials from the Department, including the Secretary, Under Secretary and Assistant Secretary, have participated in events such as Auto Shows and conferences, and have included mention of hydrogen and FCEVs. The Department's efforts to date have educated more than 12,000 teachers and 35,000 code officials and first responders specifically on hydrogen and fuel cells.

Also in 2015, the Department's Fuel Cell Technologies Office initiated a collaboration with the National Park Service to host a hydrogen fueling station at one of its facilities in Washington, D.C., as part of our technology demonstration and validation efforts. This would permit the visibility of more FCEVs in the D.C. region for public outreach events since hydrogen fuel would be available.

Finally, the Department, along with industry stakeholders, supported the celebration of the first National Hydrogen and Fuel Cells Day, designated as October 8, in recognition of the atomic weight of hydrogen (1.008). Every year, events on this day will focus on educating the public about hydrogen, the lightest and most abundant element in the universe, and the opportunities for hydrogen and fuel cells to address energy, environmental and economic security for the Nation.

Recommendation

> *"The U.S. government has an opportunity to work with infrastructure initiatives in Germany, Japan, Korea, the United Kingdom and elsewhere to collaborate on technical and regulatory issues and coordinate rollout plans; doing so would reduce costs and accelerate deployment.*
>
> *Direct DOE investment in hydrogen infrastructure in collaboration with the States and with industry would accelerate deployment in early markets, attract much-needed private investment, and yield valuable experience in achieving a national rollout.*
>
> *These efforts would be most effective if integrated with a well thought-out strategy to support both 2016 and 2025 corporate average fuel economy mileage and greenhouse gas standards recognizing that hydrogen fuel cell vehicles can play an important role by 2025 along with hybrid, battery, biofuels, and improved conventional vehicles.*
>
> *The hydrogen fueling infrastructure build-out should be part of a comprehensive National Energy Policy."*

Response

The Department recognizes the importance of collaborating on infrastructure initiatives and does so on a number of fronts.

In the previous biennial report, we reported a total of 30 partners signed on to H2USA, the public-private partnership we co-launched with our industry partners in May 2013 to address the key challenges to advancing hydrogen infrastructure. By the end of 2015, H2USA had 45 partners, including major global automakers, as well as hydrogen providers, technology developers, and trade associations representing the natural gas industry and the electric drive industry. H2USA has launched four working groups on the topics of Hydrogen Fueling Stations, Market Support and Acceleration, Financial Investment, and Locations Roadmap that are addressing many of the recommendations raised by HTAC.

The Department's Hydrogen and Fuel Cell Technologies Program also collaborates closely on state initiatives and partnerships, including the California Fuel Cell Partnership, state/industry partnerships in Ohio, Connecticut, Massachusetts, South Carolina, and Hawaii, as well as the national industry trade association, the Fuel Cell and Hydrogen Energy Association.

A major accomplishment in FY 2015 was the design and development of a station performance validation device, known as HySteP (Hydrogen Station Equipment Performance Device). HySteP will enable the rapid validation of new stations and avoid the need for automakers to individually send their vehicles to every new station to validate refueling performance and protocols. This will substantially streamline the time it takes to get stations on line and ensure that fueling protocols and performance are adequately addressed before customers refuel. HySteP addresses a key challenge in deploying infrastructure. Going forward, utilization of HySteP in the field will be coordinated with state activities.

To address international collaboration, the Department participates in the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), which includes 17 member countries and the European Commission.[5] During the period covered by this report, Japan served as Chair of IPHE, and the U.S. as Vice Chair along with Germany.

The Department's Hydrogen and Fuel Cell Technologies Program has co-organized a number of workshops specifically on hydrogen infrastructure identifying opportunities to reduce cost and improve reliability. Through DOE's national lab efforts, more than 120 hydrogen station designs have been analyzed to identify optimum configurations for cost reduction and standardization. The activities of H2USA, IPHE, HTAC, and other stakeholder input will help provide feedback towards a viable strategy for hydrogen and fuel cells.

In regard to national energy policies, the Department welcomes the Committee's continued engagement and appreciates HTAC's input into the QTR published in 2015. One specific example that includes hydrogen is the proposed 21st Century Clean Transportation Plan. This plan includes development of regional low-carbon fueling infrastructure by encouraging regional approaches involving states, local governments, universities, and private organizations. These partners will work together to define low carbon fuel deployment proposals including charging stations for electric vehicles, advanced biofuels, hydrogen fuel cells and others low-carbon options that take into account the unique economies, resources, and development needs of different regions. Deployment strategies will be encouraged to address fueling infrastructure from a systems perspective and promote adoption of innovative technologies and solutions that will help put the regions on a path to meet the goals of a 26-28 percent reduction in greenhouse gas emissions by 2025 and a more than 80 percent reduction by 2050.

With the COP21 Climate Negotiations completed in December 2015, specific policy discussion will be provided in future biennial reports outside the scope of this 2014-15 report.

[5] See www.iphe.net

Recommendation

> *"DOE's hydrogen and fuel cell research budget has shrunk by more than 50% since FY 2009, while research budgets in other countries have grown significantly; a stronger commitment to research and development would ensure U.S. technology leadership and build on the impressive current U.S. knowledge base."*

Response

The Department continues to focus on activities that will yield technology advancements in key areas. These include ongoing reductions in the cost and improvement in the durability of fuel cells; reductions in the cost of renewably produced hydrogen; and improvements in systems for storing hydrogen. Investments in the Department's Hydrogen and Fuel Cell Technologies Program are requested in the President's Budget at a level that maximizes innovation across technology areas.

The President's fiscal year (FY) 2014 budget request for the Department's Hydrogen and Fuel Cell Technologies Program was 25 percent higher than the FY 2013 request ($100 million vs. $80 million, with a final enacted amount of $92.9 million). The President's FY 2015 request maintained a high level of support for the office at the FY 2014 enacted level. This is consistent with the Administration's clean energy policies, and the Department's activities are aligned with automakers' plans for commercializing fuel cell vehicles, which began in 2015 with commercially available FCEVs from both Toyota and Hyundai.

The Department will continue to closely monitor and evaluate technology status and market potential, and sustain a balanced portfolio of high-impact investments.

IV. Recommendations from HTAC's 2013 Annual Report and Cover Letter

Recommendation

"With respect to both the highlights and concerns, the Committee suggests that the priority and future funding levels for hydrogen and fuel cell technology be increased. Increased funding is critical to progress for commercialization, research and development, infrastructure, and education, and it makes a statement about the fuel cell and technology future to the marketplace and potential investors. FCEVs and stationary fuel cells both contribute to the reliability and security of the nation's future energy system. From the Committee's perspective, we cannot achieve the potential or promise of hydrogen and fuel cell technology in the U.S. energy system at the current priority and funding levels in a time frame that is meaningful, internationally competitive, or serves the nation's interests and defends against potential threats. We know and understand the priority preference that has been demonstrated within the Department as regards battery electric vehicles (BEVs). We are aware of both the progress and near-term successes of the Program, as well as some of its challenges and difficulties. We thus recommend more priority and emphasis on FCEVs in an 'all of the above'" world for the fundamental reason that future outcomes will be 'no regrets' for doing so."

Response

The Department agrees that it is a critical time to establish a U.S. leadership position in the development, commercialization, and manufacture of hydrogen and fuel cell technologies. As mentioned in the previous recommendation response, the Department actively participates in international partnerships and continues to monitor global developments.

The Department's Hydrogen and Fuel Cell Technologies Program publishes an annual market report that assesses the state of the industry and showed more than 50,000 fuel cells shipped worldwide in 2014, a roughly 30 percent annual growth in fuel cell shipments every year since 2010. The industry just surpassed $2.2 billion in revenues by the end of 2014, signaling the emergence of a robust new industry.

Recognizing the importance of leadership in emerging clean energy technologies and the value of HTAC's recommendation, the Department launched three new projects in 2015 to develop a competitive supply chain and conduct a global competitive analysis for the fuel cell and hydrogen industry. As part of these efforts, four regional technical centers (in California, Colorado, Connecticut and Ohio) will be involved to facilitate supplier-developer engagement. A national online database will be created to enable more visibility for domestic companies.

Another key effort is the development of manufacturing quality control technologies at NREL, which will be commercialized in the coming year.

Every year, the Department's Hydrogen and Fuel Cell Technologies Program assesses the impact of its funds in enabling innovation and progress. By the end of 2015, the Department's program had enabled 580 issued U.S. patents, 45 commercial technologies, and 65 technologies that are projected to be commercial in three to five years.[6] Examples include catalysts, electrolyzers, fuel cell components, hydrogen storage tanks and other technologies to enable the successful commercialization of hydrogen and fuel cells. Through DOE-funded efforts, the cost of automotive fuel cells have been cut 35 percent since 2008 and durability has increased by a factor of 4.[7]

In terms of funding, the Department continues its stable funding commitment in support of innovation opportunities for hydrogen and fuel cells to support the President's clean energy policies. Specific budgets for fiscal years 2014 and 2015 were provided in the preceding response.

Recommendation

> *"We would be pleased if you would request a review of the HTAC's work later this year or early next year as we approach the ten-year anniversary of the Committee's formation and commissioning. The Committee has not yet had the opportunity to present its work, worth and accomplishments to the Secretary in person. We welcome an opportunity in which both you and members of your leadership team can hear and see firsthand how this Committee of energy technology and public policy expert volunteers is committed to helping shape a part of the nation's future energy system in support of the ongoing efforts of the Department and its Program Office."*

Response

The Department values the advice and commitment of the Committee in its efforts to continue improving the Department's programs and activities related to hydrogen and fuel cells. In response to the request for a formal review of HTAC, this is not necessary given the role of a federal advisory committee to provide advice to the Department. Senior members of the leadership team at the Department continue to be actively engaged with HTAC.

---

[6] http://energy.gov/eere/fuelcells/articles/fuel-cell-technologies-office-2015-recap-and-year-ahead

[7] As of the end of 2015, the high volume modeled cost based on laboratory state-of-the-art is \$53/kW vs. the target of \$40/kW by 2020 and the durability is 3,900 hours vs. the target of 5,000 hours.

V. Recommendations from HTAC's 2014 Annual Report and Cover Letter

Recommendation

"The consumer incentive to purchase fuel cell vehicles has expired just as commercial vehicles are becoming available. We encourage you to support efforts to reinstate such incentives as complementary to state initiatives so that the vehicle launch is sustained. President Obama's 2016 Budget accommodates renewal of the incentive at a level of $10,000. Your assistance in making this proposal more visible and stimulating a debate would be a valuable first step in seeing its passage.

The progress being made in California, including the creation of the re-fueling infrastructure, is an opportunity for you to bring these efforts to the attention of other states in the months and years ahead. California is committed to building an initial network of 100 hydrogen refueling stations in critical locations across the state, investing $90 million to date, anticipating approximately 40 stations constructed by the end of this year. California is further supporting introduction of vehicles by providing rebates of $5000 to each FCEV purchased or leased for a period of at least three years."

Response

To increase the visibility of President Obama's proposed tax incentive for alternatively fueled vehicles (as outlined in his FY 2016 budget request), the Department issued a publicly available fact sheet describing proposed tax credits for fuel cell electric vehicles.[8] Up to $8,000 in tax credit is now available for light, medium, and heavy-duty vehicles as part of the FY 2016 Omnibus Appropriations Act, which extended the tax incentive for fuel cell electric vehicles from December 31, 2014 to December 31, 2016. The tax credit/incentive depends on the vehicle's fuel economy, and manufacturers must follow specific procedures outlined in IRS Notice 2008-33, Credit for New Qualified Alternative Motor Vehicles, to ensure that a vehicle meets certain technical requirements. IRS Notice 2008-33 also provides guidance to taxpayers about claiming the credit.[9]

---

[8] http://energy.gov/sites/prod/files/2015/10/f27/fcto_tax_credit_fact_sheet_oct2015.pdf

[9] *See* Public Law 114-113; 26 U.S.C. §30B; IRS Notice 2008-33 is available at https://www.irs.gov/pub/irs-drop/n-08-33.pdf.

Recommendation

"Your leadership of the Quadrennial Review and its focus on infrastructure is an excellent platform upon which to offer support to fuel cells for grid resiliency and storage.

Considerable attention is being paid to hydrogen and fuel cell progress in Japan and Germany. Japan, in fact, has given hydrogen "the central role" in its low carbon energy future, and has committed more than $500 million this year for research and infrastructure deployment. The Committee remains convinced that the US has an opportunity to regain global competitiveness via increased coordination among the multiple stakeholders in the HFC community. Your active leadership together with the Department's convening authority could help re-invigorate the determination of US decision makers to keep moving forward by finding ways toward mutual support between government and private sector leaders.

Budgetary support is the perennial item we bring to your attention. The Committee is grateful for the relatively stable level of funding that has been provided in recent years. Of course we would be neglecting our advisory purpose if we did not encourage you to consider a higher level of funding commensurate with global leadership vis a vis both Japan and Germany, considering the opportunity to move more rapidly now to commercialization and the need for infrastructure to support it."

Response

Responses to this recommendation are also provided in previous responses within this report. The Department recognizes that emerging technologies face a number of obstacles and continues to pursue a balanced strategy across basic and applied research and development. We are also addressing institutional challenges, such as codes and standards and infrastructure, particularly through our public-private partnership, H2USA. As stated previously, the QTR includes discussion of opportunities for research, development, demonstration, and deployment in hydrogen and fuel cells in a number of areas.

The 2016 budget request for the Hydrogen and Fuel Cell Technologies Program was $103 million, roughly 10 percent higher than the 2015 request of about $93 million. The Office is actively involved in international collaboration and applying lessons learned from the over 200 hydrogen station deployments underway in other countries. In addition, the Department coordinates extensively through a number of state partnerships including California's initiative of $100 million for the rollout of 100 hydrogen fueling stations supporting the commercial deployment of FCEVs in the state. Leveraging both Federal and state activities has created a robust, collaborative effort spanning fundamental research to deployment to enable domestic leadership and widespread commercialization of hydrogen and fuel cell technologies.

Appendices: HTAC Letters and Reports

A. Hydrogen Enabling Renewables Working Group Summary Report and Department of Energy Response

B. Hydrogen Infrastructure Letter and Department of Energy Response

C. HTAC's 2013 Annual Report and Cover Letter and Department of Energy Response

D. HTAC's 2014 Annual Report and Cover Letter and Department of Energy Response

Hydrogen & Fuel Cells Technical Advisory Committee

Hydrogen Enabling Renewables Working Group

Summary Report

October 2013

Introduction

In late 2010, the Hydrogen & Fuel Cell Technical Advisory Committee chartered a working group to examine the various ways in which hydrogen might serve as an enabler for high penetrations (greater than 50% nationally, or regionally, on an energy basis) of variable renewable energy in the United States. The Hydrogen Enabling Renewables Working Group (HERWG) began work in earnest in early 2011.

Comprised of both HTAC members and other representatives with significant hydrogen and fuel cell expertise, the Working Group benefited from the extensive knowledge, experience and insights of the following members:

- Frank Novachek (HTAC Member – Working Group Lead)
- Peter Bond (HTAC Member)
- Charles Freese (HTAC Member)
- Rob Friedland (Industry)
- Monterey Gardiner (DOE)
- Fred Joseck (DOE)
- Maurice Kaya (HTAC Member)
- Harol Koyama (HTAC Member)
- Jason Marcinkoski (DOE)
- Todd Ramsden (NREL)
- Bob Shaw (HTAC Member)
- Darlene Steward (NREL)
- George Sverdrup (NREL)
- Sandy Thomas (Consultant)
- Levi Thompson (HTAC Member)
- Daryl Wilson (Industry)

The first task was describing the future scenario where the US combined electric grid and transportation sector were powered with more than 50% renewables nationally or regionally on an energy basis. After significant discussion, the Working Group envisioned an environment characterized by the following attributes:

- Large amounts of variable off-peak renewable energy result in significant "spillage" or curtailments when it exceeds energy demand.
- Reductions seen in the cost of renewable energy versus traditional energy sources due to high volume production and technological advances
- Baseload power plants with lower turndown capabilities and better load following performance
- Large wind resources not near large load centers, requiring significant transmission investments
- Environmental concerns and transmission constraints limiting large scale central solar facilities, thereby influencing more distributed scale solar, using existing urban and suburban open spaces, including paved lots. (This type of resource will likely be interconnected to distribution grids).

- Distributed and utility-scale generators, such as stationary fuel cells, possibly becoming more economical and more efficient (both from energy conversion and CO2 perspectives) than traditional utility scale thermal resources.

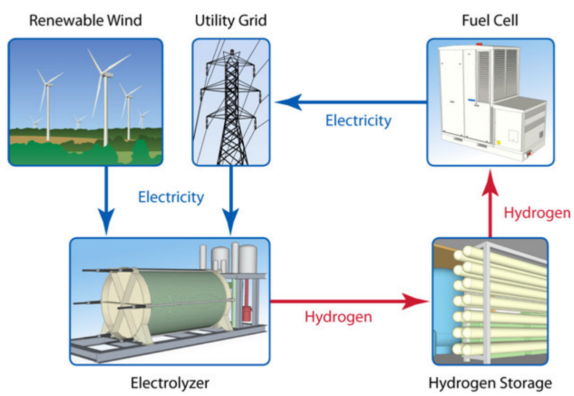
Given this potential future, the Working Group identified several potential applications for hydrogen and fuel cells to enable high penetrations of renewables, including:

- As a means for storing excess renewable energy and returning that energy to the electric grid when needed,
- As a supplement to natural gas system using excess renewable energy for hydrogen production to mix with natural gas,
- As an alternative energy transmission and distribution mechanism, and
- To improve renewable resource utilization through the production of vehicle fuel using excess renewable energy.

Because the elements of energy storage represent the fundamental building blocks for the other applications, the Working Group focused its attention in that area.

Energy Storage for Wind Integration

To better understand the economic drivers for hydrogen energy storage systems, the Working Group developed two basic models for evaluating hydrogen energy storage against other competing storage technologies. The first was a "Simple Model" based on the basis scheme shown below for utility scale wind energy storage:

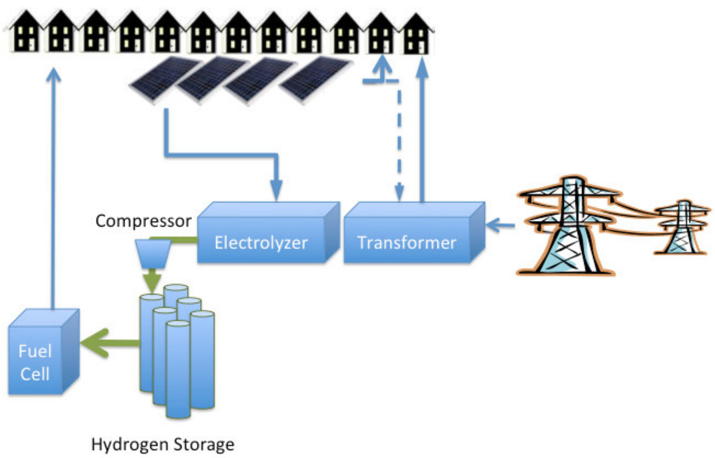


A whitepaper discussing the results of the analyses conducted using this model was developed by Dr. C.E. "Sandy" Thomas and is included as Appendix 1: Energy Storage for High Penetration Wind.

The conclusions from the "Simple Model" analyses found that hydrogen energy storage is competitive with all current energy storage technologies when the economic conditions make the capture of large amounts (on the order of weeks) of otherwise curtailed wind energy more valuable than curtailing it and letting the generation potential go to waste in order to maintain electric system stability and control. All in the Working Group agreed that such economic conditions could exist in the "high wind penetration" scenario contemplated (i.e., greater than 50% nationally, or regionally, on an energy basis), especially if coupled with higher renewable portfolio standards and/or other policies favoring renewable energy.

Community Energy Storage Systems for Load Leveling Solar Photovoltaics and Vehicle Refueling

The second was a model for evaluating community scale solar energy storage based on the following scheme:



A whitepaper discussing the results of the analyses conducted using this model was developed by Darlene Steward, from the National Renewable Energy Laboratory and is included as Appendix 2: Community Energy: Analysis of Hydrogen Distributed Energy Systems with Photovoltaics for Load Leveling and Vehicle Refueling.

The "Community Energy Model" analyses produced the following conclusions:

- There is a surprisingly good match between building load, PV system peak capacity and the number of vehicles that would be served in that size of community.
- Although results do not show a clear advantage for hydrogen energy storage load leveling or vehicle refueling, the economics could become competitive with larger systems (on the order of 15,000 kW peak capacity PV systems).
- The additional equipment for the hydrogen system hurts the economics for smaller systems.
- The flexibility of the hydrogen system configuration improves the economics for larger systems.
- For both hydrogen and electric vehicles, diverting more electricity from the PV system improves the economics, but the effect is more pronounced for the hydrogen system.

Other Energy Storage Approaches

Near the end of the of the Working Group's efforts, new information was being discussed about approaches to storing renewable energy as hydrogen in the nation's existing natural gas system. In Europe there are now more than twenty so called "power-to-gas" hydrogen energy storage demonstration projects which have been launched in the last 18 months – more than any other technology platform for utility scale storage. Though the Working Group did not delve into this hydrogen storage pathway in significant detail, the concept is intriguing to several of its members and could possibly have applications for the U.S.

Overall Conclusions & Recommendations

As the nation's renewable generating capacity (solar and wind) expands to deliver a significant fraction of the total electric energy generated (somewhere greater than 30 percent on an energy basis nationally), both short and long term energy storage will likely be very desirable, if not required. The Working Group considered a scenario where the penetration of renewables was 50% on an energy basis. Under this scenario, the Working Group assumed that environmental policies would likely be in place influencing grid economics to maximize the use of renewable energy, such that using curtailment as a means to maintain grid stability would be much a much more costly control measure than it is today. If that is the case, there would conceivably be economic benefits to storing weeks or more of otherwise curtailed renewable energy during peak output periods in high penetration renewable regions for use during periods when the stored renewable energy can be delivered in order to reduce the need for greenhouse gas emitting generation.

Hydrogen technology, as shown by "Simple Model" study (Appendix 1), has the most economical and greatest storage capacity for absorbing and redeploying energy generated from renewable generation when compared to batteries, compressed air energy storage and pumped hydro storage solutions, when the storage requirement is in terms of weeks or longer. Because of this, hydrogen energy storage could be an essential contributor to enabling renewables at the high penetrations contemplated by the Working Group.

Although results do not show a clear advantage for hydrogen energy storage load leveling or vehicle refueling at smaller scales studied in this effort, the economics could become competitive with larger systems, especially for larger systems (on the order of 15,000 kW peak capacity PV systems). Such a system would also be capable of providing both fully renewable fuel and electric grid stabilization benefits.

Continuing assessment of the economic viability of hydrogen production as a renewable energy storage pathway should be a high priority for DOE and the renewable/electric industry, working in partnership.

Recommendations

Energy Storage for Wind Integration:

- Determine if there are national policies being considered that would significantly increase renewable penetrations as a means to reduce greenhouse gas emissions.
- Conduct system analyses including and excluding long-term storage using policy scenarios identified, and from these analyses, estimate the value of hydrogen energy storage to the overall system under those scenarios.
- Determine what value the government could assign to otherwise curtailed renewables to make multi-day/week scale hydrogen (and other) energy storage economical.

Community Energy for Load Leveling and Vehicle Fueling:

- Conduct sensitivity analyses to determine what conditions are necessary for a hydrogen system to compete with electric battery system for fueling FCV and EV vehicles, respectively, with solar PV energy.
- Determine the community scale at which hydrogen storage competes with battery storage for solar PV load leveling and vehicle fueling.

Other

- Consider investigating potential U.S. applications for "power-to-gas" energy storage systems and, if deemed to have potential, initiate a dynamic economic study (supported by the relevant teams at DOE, the national laboratories) to evaluate the system wide and integrative benefits of such hydrogen storage system for U.S. markets.

Appendix 1

Energy Storage for High Penetration Wind

Dr. C.E. "Sandy" Thomas

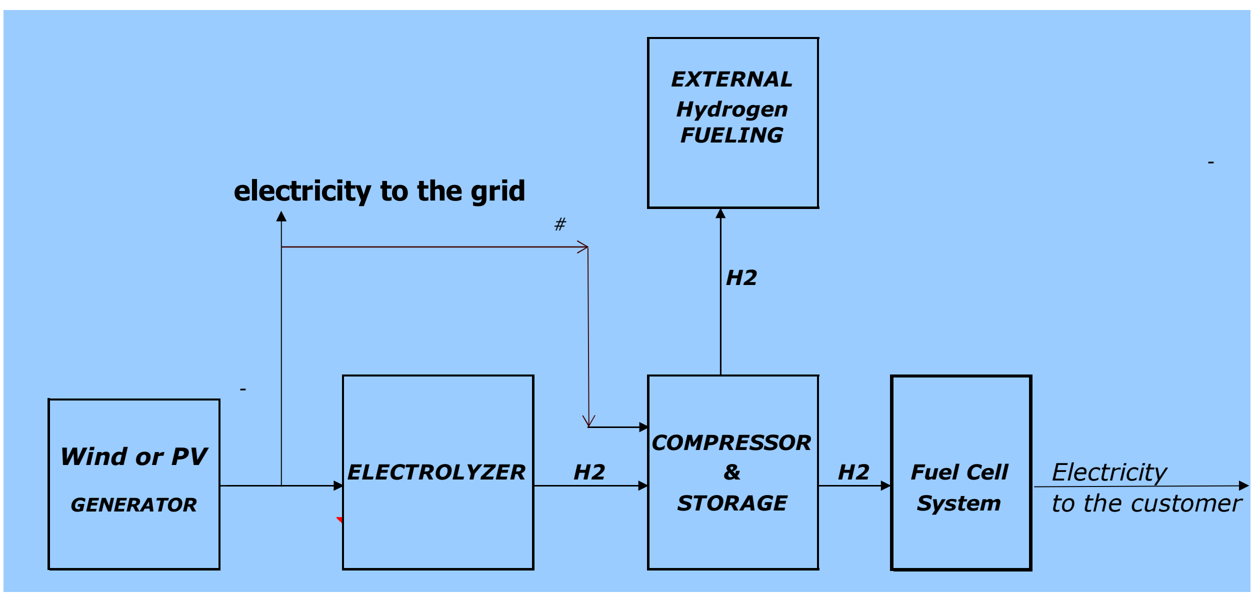
Energy Storage for High Penetration Wind

Introduction -

This work was conducted on behalf of an HTAC subcommittee chartered with the task of determining if hydrogen storage would enable wider grid penetration[1] of intermittent renewable energy sources. Both solar energy and wind farm systems would benefit from large-scale energy storage due to three factors, especially with large utility grid penetration of intermittent renewables:

- Renewable energy utilization is often limited by **electrical transmission line constraints** between the source and the electrical demand.
- Renewable energy use is sometimes limited by the **lack of adequate electricity load** at the time of large renewable generation potential.
- The fossil **fuel generators** (typically natural gas turbines) used to "Firm" intermittent renewable sources **can increase greenhouse gas emissions and local pollution** including increased NOx and SOx emissions compared to using those fossil sources all the time.[2]

The basic flow diagram for the model is shown below; renewable electricity is used to generate hydrogen with an electrolyzer. That hydrogen is then stored and either used to fuel vehicles or to generate electricity at a later time. Thus excess renewable electricity can be stored for later use instead of wasting this electricity when there is no load or when transmission capacity is limited.



[1] The hydrogen enabling renewables working group (HERWG) chaired by Frank Novachek of Xcel Energy
[2] For example, Post speculates that GHGs, NOx and SOx emissions from natural gas turbines operating at part power (where efficiency decreases) used to fill in the gaps in intermittent renewable generators may be higher with the intermittent renewable plus gas turbine than for a system that uses a NG turbine to supply 100% of the load; in this case, adding renewables may actually degrade the environment.; storing the excess renewable energy as hydrogen and "firming" intermittents with hydrogen-generated electricity would eliminate this possibility. (see: Willem Post, "Wind energy does little to reduce GHG emissions," available at http://theenergycollective.com/willem-post/64492/wind-energy-reduces-co2-emissions-few-percent .

This report compares three types of bulk energy storage:

- Battery storage
- Hydrogen storage
- Compressed air energy storage (CAES)

We do not address pumped hydro storage, since sites to store large reservoirs of water are limited.

Wind Energy

Wind energy is the most problematic, since wind resources tend to peak at night in the winter months, while electrical loads typically peak in late summer afternoons.

Y. H. Wan of NREL has explored multi-year wind output data from four wind farms at these locations[3]:

- Lake Barton, Minnesota (104 MW peak power)
- Storm Lake, Iowa (113 MW peak)
- Blue Canyon, Oklahoma (75 MW)
- Trent Mesa, Texas (150 MW)

To back up these intermittent wind sources with hydrogen storage, the fuel cell output power should be at least equal to the average wind power. The average capacity factor for wind farms in the US was 33% according to data from 2011[4]. Thus the average wind power would vary between 25MW and 50 MW, so the fuel cell system used to convert stored hydrogen back to electricity should have a peak power rating of at least 25MW or larger for higher power wind farms; we use 25-MW fuel cell systems in this model.

Battery and CAES Input Data

The battery data for this model were taken from an EPRI report[5]. The CAES (compressed air energy storage) data were taken from another EPRI presentation[6].

[3] Y. H. Wan, *Long-Term Wind Variability*, NREL/TP=5500-53637, January 2012; available at: http://www.nrel.gov/docs/fy12osti/53637.pdf

[4] R. Wiser & M. Bolinger, *2011 Wind Technologies Market Report*, Lawrence Berkeley Laboratory, August 2012; - available at: http://www1.eere.energy.gov/wind/pdfs/2011_wind_technologies_market_report.pdf -

[5] D. Rastler, *Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs, & Benefits*, - Electric Power Research Institute, Report # 1020676, December 2010, Table 4; available at: - http://large.stanford.edu/courses/2011/ph240/jiang1/docs/rastler.pdf

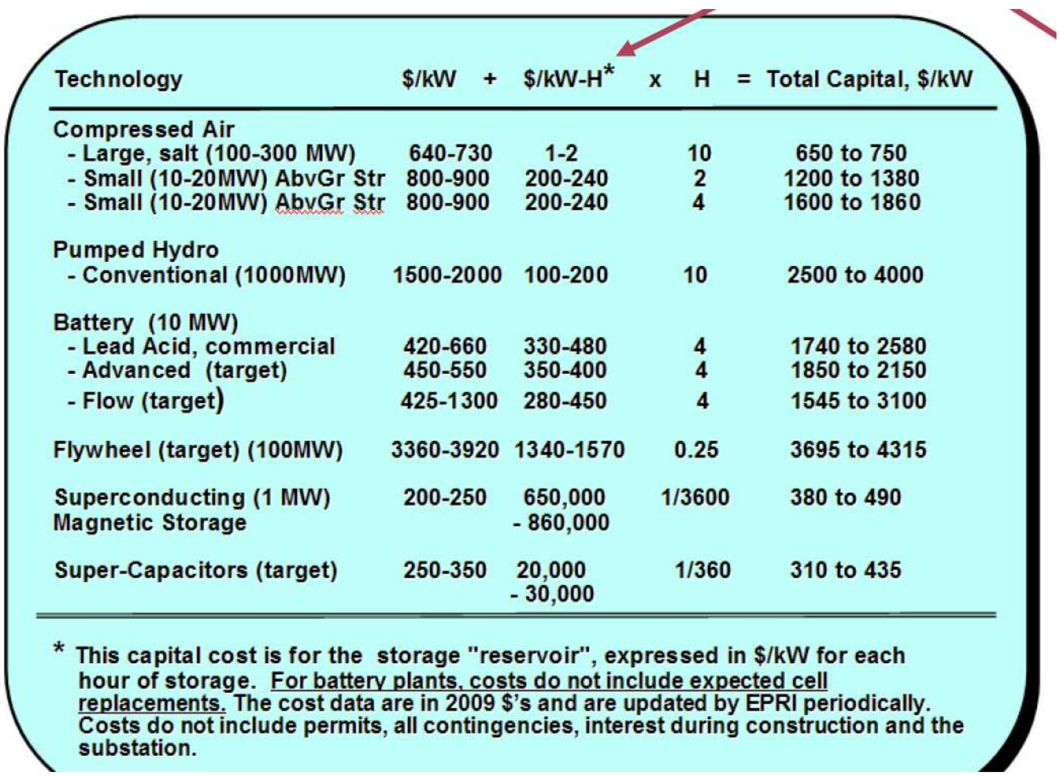
[6] R. Schainker, *Compressed Air Energy Storage (CAES)-Executive Summary*, (Electric Power Research Institute), August 2010, Slide #8, shown on the next page, available at http://disgen.epri.com/downloads/EPRI%20CAES%20Demo%20Proj.Exec%20Overview.Deep%20Dive%20Slides.by%20R.%20Schainker.Auguat%202010.pdf

Table 1. Model input data for battery and compressed air energy storage systems[7]

	$/kW		$/kWh		Efficiency	
	Low	High	Low	High	Low	High
Adv PbA	950	1590	425	475	90%	85%
Zn /Br	1450	1750	290	350	60%	60%
Fe/Cr	1800	1900	360	380	75%	75%
Zn/Air	1440	1700	290	340	75%	75%
NaS	3100	3300	520	550	75%	75%
CAES-Above	800	900	200	240	90%	90%
CAES-below	640	730	1	2	90%	90%
Li-Ion	1085	1550	900	1700	92%	87%

HTAC simple model EPRI(Rev10-9-12-25MW).XLS, WS 'Battery Data' H-13;11/2/2012

Two different cost methodologies were used in these EPRI reports: the battery cost data depend only on the energy ($/kWh) costs times the stored energy[8], while the CAES data from Schainker depend on both the power level and the energy stored.



Technology	$/kW	+	$/kW-H*	x	H	=	Total Capital, $/kW
Compressed Air							
- Large, salt (100-300 MW)	640-730		1-2		10		650 to 750
- Small (10-20MW) AbvGr Str	800-900		200-240		2		1200 to 1380
- Small (10-20MW) AbvGr Str	800-900		200-240		4		1600 to 1860
Pumped Hydro							
- Conventional (1000MW)	1500-2000		100-200		10		2500 to 4000
Battery (10 MW)							
- Lead Acid, commercial	420-660		330-480		4		1740 to 2580
- Advanced (target)	450-550		350-400		4		1850 to 2150
- Flow (target)	425-1300		280-450		4		1545 to 3100
Flywheel (target) (100MW)	3360-3920		1340-1570		0.25		3695 to 4315
Superconducting (1 MW) Magnetic Storage	200-250		650,000 - 860,000		1/3600		380 to 490
Super-Capacitors (target)	250-350		20,000 - 30,000		1/360		310 to 435

* This capital cost is for the storage "reservoir", expressed in $/kW for each hour of storage. For battery plants, costs do not include expected cell replacements. The cost data are in 2009 $'s and are updated by EPRI periodically. Costs do not include permits, all contingencies, interest during construction and the substation.

Figure 1. CAES cost data; Slide #8 from the R. Schainker presentation (reference 5 above)
[Battery cost data from this slide were not used in this model.]

[7] The Li-ion battery costs were taken from the EPRI multi-megawatt systems for "energy storage for Utility T&D support applications"; their Li-ion costs for energy storage for "ISO fast frequency regulation and renewables integration" were even higher at $4,340/kWh to $6,200/kWh, all taken from the EPRI Table 4 in reference 5 above.
[8] EPRI apparently folded in the power demand charges into an overall $/kWh cost estimate.

Hydrogen System Input Data

Table 2. Input data for hydrogen/FC storage system coats and efficiencies

	Near- term	medium-term	Long-term
*Electrolyzer HHV efficiency**	79.3%	81.7%	87.7%
*Electrolyzer Capex***	$1500 /kW	$1000 /kW	$380 /kW
Compressor efficiency	92%	92%	92%
Compressor Capex ($/kg/day)	232	232	232
FC HHV efficiency	39.7%	44.8%	49.0%
*FC capex****	$1000 /kW	$750 /kW	$500 /kW
H2 (above ground) tank capex	$807 /kg	$760 /kg	$700 /kg
H2 (below ground) Storage capex ($/kg)	2.5 to 7	2.5 to 7	2.5 to 7
H2 Dispenser Capex	$ 75,000	$ 60,259	$ 50,216

** Norsk Hydro 50.7 kWh/kg = 77.7% HHV eff.; Giner/ProtonOnsite: 88.9%*

*** NREL Independent Panel Review; (BK-6A1-46676; Sept 2009)*

****DOE Targets: $750/kW (2008); $650/kW (2012); $550/kW(2015); $450/kW (2020)*

HTAC ERWG simple model EPRI (Rev 10-9-12 - 25MW).XLS, WS Assumptions D16;12/13/2012

The below-ground storage costs are based on geologic storage in underground caverns, acquifiers or depleted natural gas fields. The total system storage costs were provided by the National Renewable Energy Laboratory[9]; these costs vary with the total storage capacity as shown in Figure 2 from $2.50/kg for very large caverns holding more than 4 million kgs of hydrogen to $7/kg for storage of less than 350,000 kg of hydrogen.

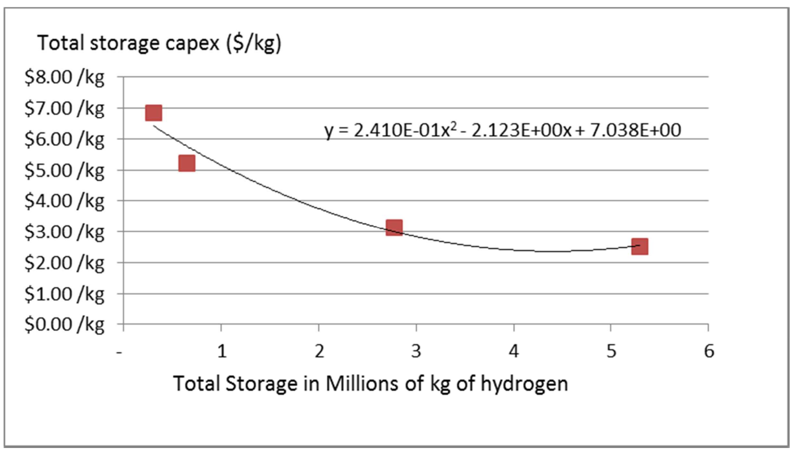


Figure 2. Underground (cavern) hydrogen storage costs as a function of storage capacity

[9] Private communication from Darlene Steward at NREL

Table 3.Annual O&M and Replacement input data

	Replacement Costs		
	Replacement Interval	Fraction Replaced	Annual O&M
	(Years)		(% of Capex)
Electrolyzer	7	25%	2.18%
Compressor	10	100%	2.50%
Storage System			0.02%
Fuel Cell System	15	30%	2.00%
Dispenser System			0.90%

HTAC simple model EPRI (Rev 10-9-12--25MW).XLS, WS 'O&M' D-13;11/9/2012

Model Assumptions

The model assumes that the owner of the energy storage system pays 5.4 cents/kWh to purchase wind power. The owner then stores the energy, and regenerates electricity when demand is high, selling that peak power electricity at a rate that will earn a 10% real, after-tax return on the storage system investment.

Table 4. Financial input data for the model

Inflation rate	1.9%
Marginal income tax rate	38.9%
Real, after-tax Rate of return required	10%
Depreciation schedule	Declining balance
Annual capital recovery factor	11.79%

HTAC simple model EPRI (Rev 10-9-12--25MW).XLS, WS 'Dashboard (Flow Diagram) D-94;11/9/2012

Stored Electricity Price Estimates from various storage systems -

The stored electricity costs were set to pay for all operating costs[10] for the storage system including the purchase of the wind energy at a price of 5.4 cents/kWh, the capacity-weighted average cost[11] of US wind in 2011 plus an extra amount such that the owner of the storage system earns a 10% real, after-tax

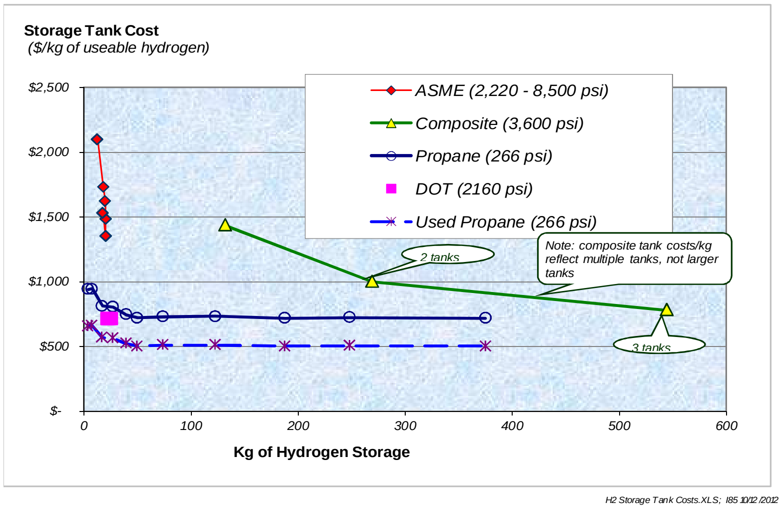


Figure 3. Examples of above-ground hydrogen tank costs circa 2009

return on the investment in the storage system. The price of electricity is set to assure this 10% real ROI with the economic parameters in the model. (Table 4). With the battery & hydrogen storage system data, the estimated costs for electricity generated from stored energy are summarized in Figure 4. The scale is expanded in Figure 5 to show the lower cost storage systems (excluding the high-cost Li-ion system.) Two costs are shown for the battery and CAES storage systems, corresponding to EPRI's high and low cost estimates.

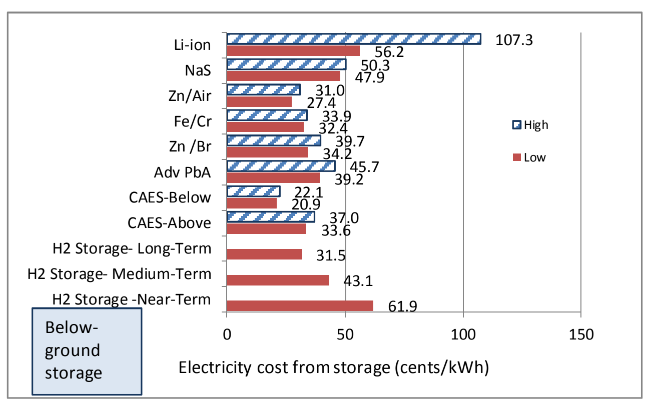


Figure 4. Cost of stored electricity (one day's storage) with natural gas at $7/MBTU (used for CAES only)

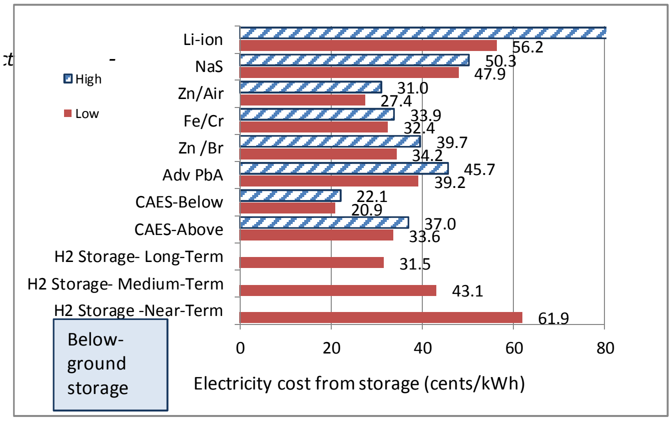
[10] Annual O&M and periodic replacement costs for electrolyzers, fuel cells, compressors, etc.; taxes and insurance; - construction loan costs (first year only; two-year construction period assumed). -

[11] See reference #3 -

The potential lowest cost system according to the EPRI report is the Zn/Air system that is not currently commercially available. The long-term hydrogen storage system cost at 31.5 cents/kWh is competitive with the future Zn/air battery system at 27.4 to 31 ₵/kWh, and less than the current commercial battery systems (Li-ion, NaS and PbA)[12].

Figures 4 & 5 are for underground (cavern storage of hydrogen). As shown in Figure 6, above-ground storage in pressurized hydrogen tanks is also economic. Above-ground storage offers more flexibility, since it does not require location near geologically available underground sites. Hydrogen storage in tanks is competitive in the long-term (33.2 cents/kWh) with current commercially available battery systems such as Li-ion, NaS and PbA. Hydrogen long-term costs are also less than above-ground CAES storage systems.

The hydrogen storage tank cost estimate for the long-term ($700/kg) could be based on either low-pressure propane tanks that are priced at $724/kg new or $506/kg (used) as shown on Figure 3 or existing Lincoln Composites "Titan" composite hydrogen tanks that were selling for $700/kg in quantities of three in 2009.



HTAC simple model EPRI(Rev10-9-12-25MW).XLS, WS 'DashBoard' AM-315;11/12/2012

Figure 5. Cost of stored electricity to yield 10% RATROI (Same as Figure 4 with expanded scale)

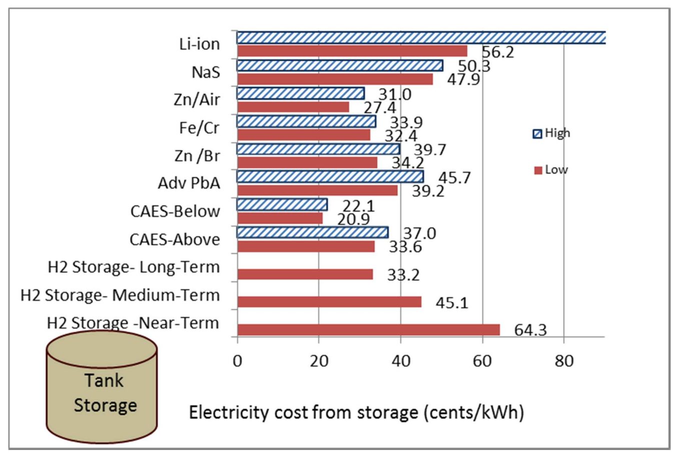


Figure 6 . Stored electricity costs for above-ground hydrogen storage in tanks (one day's storage)

<u>Need for longer-term storage</u>

Energy storage times longer than one day are highly desirable for wind energy. For example, Figure 7 shows the spectra of wind energy from one source[13]. In addition to the spectral peak at one day duration, there is a dominant peak at 4 day intervals, but this 4-day peak is usually associated with sites near an ocean. And there is a dominant peak at one year, indicating a strong annual oscillation in wind energy, peaking in the winter and diminishing in the summer months.

[12] Note that all hydrogen electricity prices quoted here should be compared with peak electricity rates, since the electricity generated from stored hydrogen can be supplied during peak demand periods.
[13] Source: Green Rhino Energy http://www.greenrhinoenergy.com/renewable/wind/wind_characteristics.php

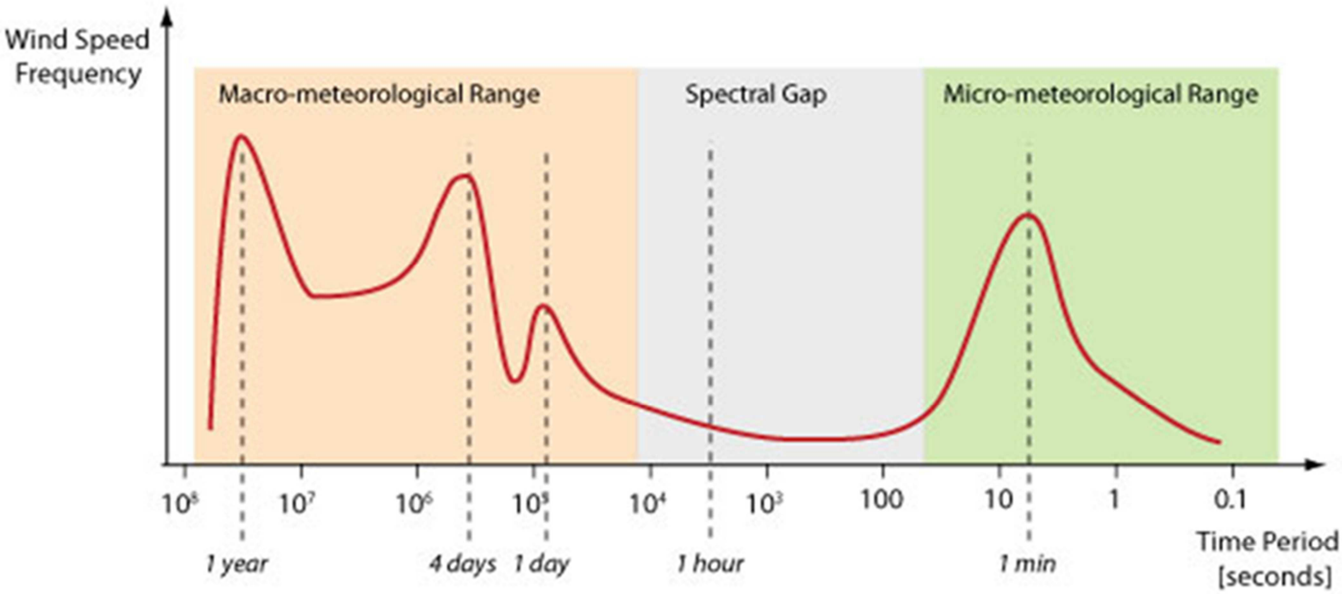


Figure 7. Spectral energy distribution for wind energy

Specific wind annual energy profiles[14] are shown in Figures 8-11. Figure 8 shows 10 years data and the 10-year average for a 104-MW wind farm in Lake Benton, Minnesota. The average peak wind energy in the winter is 1.64 times the annual wind energy in the summer months. Note also that the annual peak to minimum wind energy often varies much more than the 10-year average.

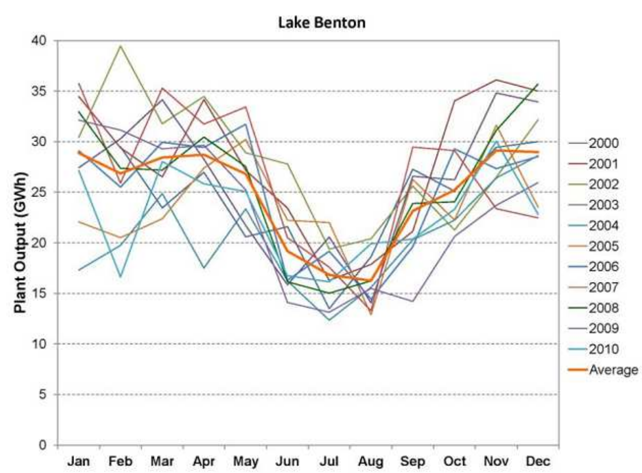


Figure 8.Ten years of wind energy produced at the 104-MW Lake Benton, Minnesota wind farm (winter wind averages 1.6 time summer wind)

Figure 9 shows 7 years' wind energy data from the 75-MW wind farm at Blue Canyon, Oklahoma. The 7-year average - has a peak winter energy level that is **2 times** the summer energy level, again with large annual deviations from the average.

Finally, Figure 10 shows similar annual data for a 113-MW wind farm at Storm Lake, Iowa, where the winter peak energy output is **2.4 times** the average winter energy output.

From these data it is apparent that there would be significant advantage if the excess winter wind energy could be stored until the summer months, when demand is typically higher to meet air conditioning loads.

[14] See Reference #1 (Wan)

Wind energy is also frequently higher at night than during the day, as illustrated in Figure 11 for a 150-MW wind farm in Trent Mesa, Texas.

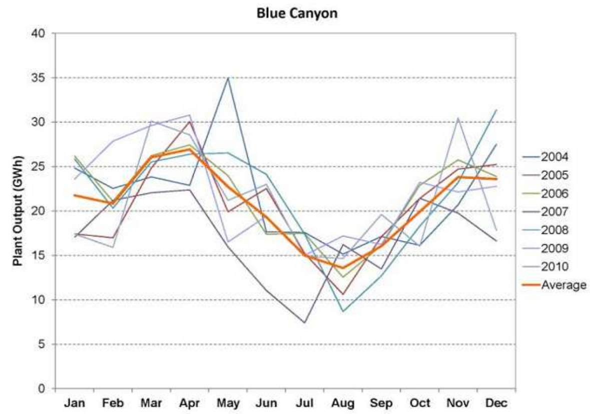


Figure 9. Seven years of wind energy data from the 75-MW Blue Canyon, Oklahoma site (winter energy is 2 times the summer wind energy)

<u>Stored electricity costs as a function of storage time</u>

The required price of stored electricity to achieve the 10% ROI goal are shown in Figure 12 as a function of the storage time. For a few days of storage, hydrogen storage is less expensive than the lowest cost battery option (Zn/air), even for the near-term hydrogen system. For storage times longer than 6 days, the long-term hydrogen costs are less than the cost of CAES storage with natural gas at \$7/MBTU[15].

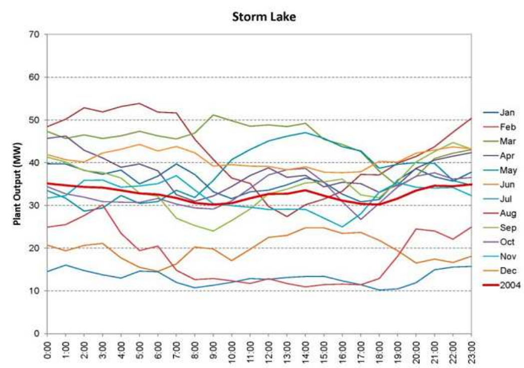


Figure 10. Ten years of wind energy data from the 113-MW Storm Lake, Iowa wind farm (Winter wind energy is 2.4 times the summer wind energy)

US Natural gas prices have been trending down with the discovery and production of gas from shale formations as shown in Figure 13 for industrial users, with industrial gas prices falling below \$4/MBTU. However, the EIA in their latest (2012) Annual Energy Outlook is projecting that industrial gas prices will rise[16] as shown in Figure 14. projecting future prices in the \$4.50/MBTU to \$8/MBTU range.

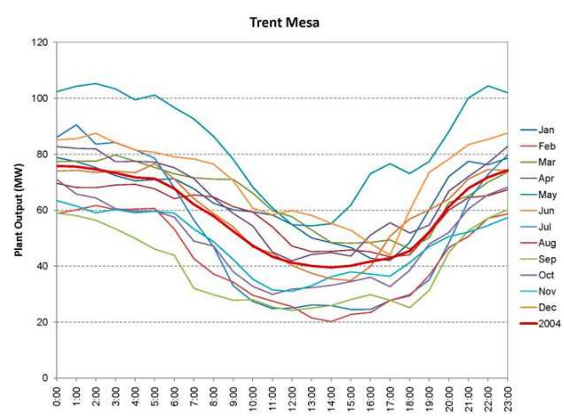


Figure 11. Average hourly wind energy at Trent Mesa, Texas, showing more wind energy at night than during the day

The impact of lower natural gas prices on the stored electricity prices from CAES is shown in Figure 15. Even if natural gas fell to \$3/MBTU,

---

15 Natural gas is used to heat the compressed air gas in curr

16 John Hofmeister (the former President of Shell Oil USA an and fuel cell Technology Advisory Committee), points out th as high as 50% per year, indicating that these wells will have to be replaced (or re-fractured) frequently to keep the gas flowing, thereby increasing shale gas costs over time.

hydrogen storage would be less expensive than CAES for storage times longer than 60 days in the near-term; 30 days in the mid-term, and 14 days in the long-term as shown in Figure 15. Note again that these prices for stored energy should be compared with peak electricity rates, since the stored energy can be sold at any time.

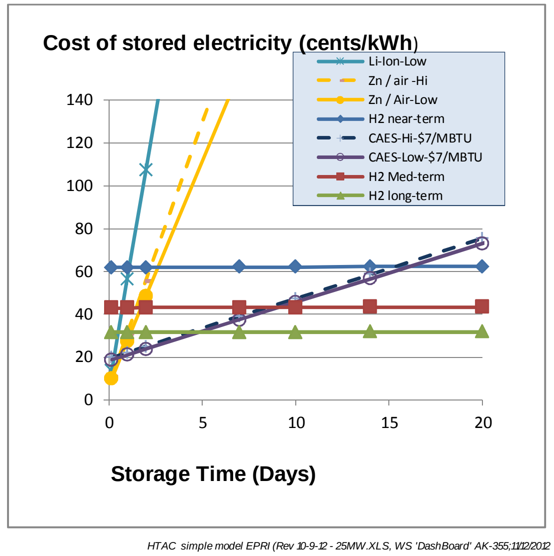


Figure 12. Electricity price to earn 10% ROI for longer term storage with natural gas at $7/MBTU

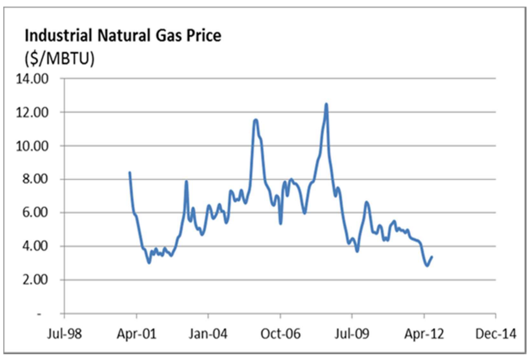


Figure 13. Recent US Industrial Natural Gas Prices

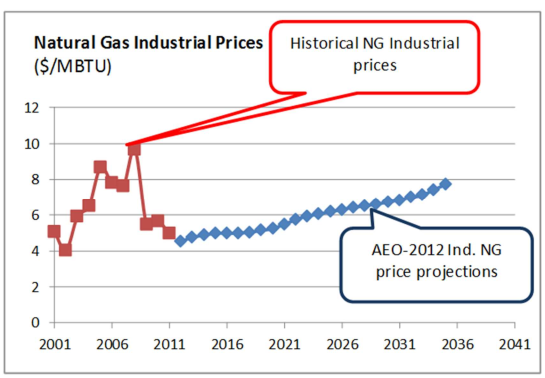


Figure 14. Industrial natural gas prices projected by the EIA in their 2012 Annual Energy Outlook (AEO)

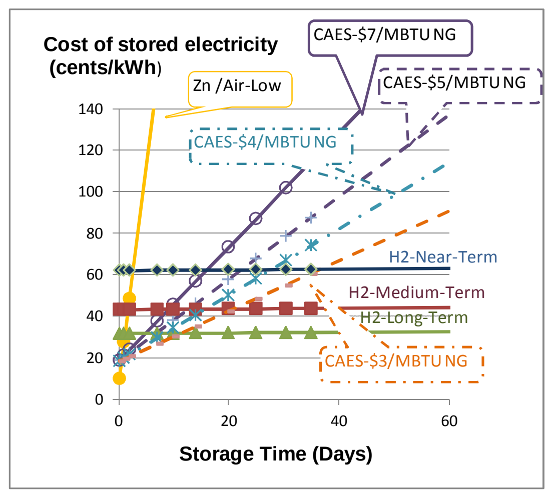


Figure 15. Stored electricity prices to yield a 10% real, after-tax ROI including variable natural gas prices for CAES storage; both hydrogen and CAES prices are for underground storage.

<u>Longer-Term Hydrogen CHHP systems</u>

In the future, high temperature stationary fuel cells such as molten carbonate (MCFCs), phosphoric acid fuel cells (PAFCs) or solid oxide fuel cells (SOFCs) could provide extra revenue to the storage system owner by supplying both heat and hydrogen—combined heat, hydrogen and power (CHHP) systems. We consider four estimates for future SOFC costs:

1. Strategic Analysis has estimated a mass production cost of $700/kW for 100kWe SOFC systems,

2. - the HTAC subcommittee has chosen \$500/kW as the long-term price estimate for FC systems,
3. - the DOE's SECA has set a "stretch" target of \$400/kW for SOFCs, and
4. - Rivera-Tinoco et al. have estimated a SOFC manufactured cost[17] of \$100/kW or less for 250 kW modules for cumulative production volumes less than 1 MW as shown in Figure 16. This is the manufactured cost estimate, based on inputs from three fuel cell companies[18]. To this we add a multiplier factor of 1.5 to arrive at an estimate of the selling price[19] that the hydrogen storage operator would have to pay, or an estimated long-term price of \$150/kW for an advanced SOFC system in production.

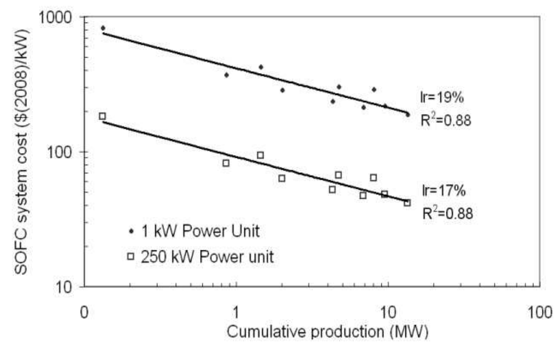


Figure 16. Estimated manufacturing *cost* for SOFC systems by Rivera-Tinoco et al.

Strategic Analysis has estimated the mass production costs of Stationary PEM and SOFC systems (Table 5)[20]. They are projecting that 100-kWe low temperature PEM fuel cell systems (including reformer and AC inverter) could be produced for \$771/kWe, and costs as low as \$402 to \$440/kWe for 100 kWe SOFC systems might be achieved in very

Table 5 . Strategic Analysis estimated costs of stationary fuel cell systems in mass producion.

LT PEM Systems	1 kWe	5 kWe	25 kWe	100 kWe
100 sys/yr	\$10,106	\$3,182	\$1,180	\$771
1,000 sys/yr	\$7,854	\$2,556	\$941	\$637
10,000 sys/yr	\$6,618	\$2,185	\$760	\$486
50,000 sys/yr	\$6,032	\$1,935	\$658	\$428
HT PEM Systems	**1 kWe**	**5 kWe**	**25 kWe**	**100 kWe**
100 sys/yr	\$10,130	\$3,483	\$1,363	\$1,062
1,000 sys/yr	\$7,895	\$2,840	\$1,181	\$867
10,000 sys/yr	\$6,699	\$2,448	\$941	\$680
50,000 sys/yr	\$6,101	\$2,132	\$816	\$606
SOFC Systems	**1 kWe**	**5 kWe**	**25 kWe**	**100 kWe**
100 sys/yr	\$11,830	\$3,264	\$981	\$532
1,000 sys/yr	\$6,786	\$2,168	\$671	\$440
10,000 sys/yr	\$5,619	\$1,862	\$599	\$414
50,000 sys/yr	\$5,108	\$1,709	\$570	\$402

Figure 5: Summary Table of System Cost Results, \$/kWe

[17] R. Rivera-Tinoco, K. Schoots & B.C.C. van der Zwaan, *Learning Curves for Solid Oxide Fuel Cells* (Energy Research Center of the Netherlands.), Figure 4; available at: http://www.energy.columbia.edu/sitefiles/file/Learning%20Curves%20for%20Solid%20Oxide%20Fuel%20Cells.pdf

[18] HC Starck, Topsoe and Versa. -

[19] This 1.5 multiplier assumes that 80% of the production cost is purchased parts and materials with a 20% General - & Administrative (G&A) markup, and labor has a 25% G&A markup plus a 40% overhead markup, and the sum of all - these costs is marked up by 15% to account for profit; the net result is a 1.5 times markup on the manufactured - cost to obtain a price. -

[20] Brian James, Andrew Spisak & Whitney Colella, "Manufacturing Cost Analysis of Stationary Fuel Cell Systems," - Strategic Analysis, Arlington, Virginia September 2012. -

large production volumes (1,000 to 50,000 systems per year.)

For these longer term systems, we have also reduced the estimated cost of the electrolyzer based on the 2009 NREL independent review of electrolyzer costs[21]. The NREL independent review used data from six electrolyzer companies[22] and reported a manufacturing cost estimate of $380/kW for an electrolyzer supplying 1,500 kg/day, but this cost also included the compression, storage and dispensing equipment at the fueling station. The DOE's H2A model lists a total cost of $1.263 million for the electrolyzer, transformer/rectifier and other electrolyzer balance of plant, out of a total cost of $2.254 million; so the electrolyzer system accounts for 56% of the reported cost of $380/kW. Applying this factor implies an electrolyzer system cost of$213/kW, or an estimated price of $320/kW after applying our 1.5 markup factor to translate manufacturing *cost* to selling *price* to the hydrogen storage system operator. In addition, Sunita Satyapal, the DOE's Hydrogen Program Manager, announced at the 2011 Annual Merit Review[23] that Giner and Proton had demonstrated an electrolyzer production cost of $350/kW. The assumptions for these SOFC systems are compared with the base case hydrogen long-term data in Table 6 (See Table 2 for the cost and efficiency assumptions for the Near- and Medium-Term hydrogen options.)

Table 6. cost and efficiency values used for three different long-term hydrogen storage scenarios

Long-Term Hydrogen Assumptions	Base Case	SOFC-Low	SOFC-High
FC Capex	$500 /kW	$150 /kW	$700 /kW
FC HHV Efficiency	49.0%	55.0%	55.0%
Electrolyzer HHV Efficiency	87.7%	87.7%	87.7%
Electrolyzer Capex	$380 /kW	$320 /kW	$320 /kW

HTAC simple model EPRI (Rev 10-9-12 -25MW).XLS, WS Assumptions D47; 11/11/2012

<u>Hydrogen Fuel Revenue</u>

[21] J. Genovese, K. Harg, M. Paster, & J. Turner, *Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis*, NREL/BK-6A1-46676, September 2009. -

[22] Avalence, Giner, H2 Technologies, Hydrogenics, IHT and Proton Energy (now called Proton Onsite) -

[23] As reported by Sunita Satyapal in her 2011 AMR presentation, available at: - http://www.hydrogen.energy.gov/pdfs/review11/pl003_satyapal_joint_plenary_2011_o.pdf

In addition to supplying electricity, the hydrogen storage system can provide fuel for fuel cell electric vehicles (FCEVs). In general, hydrogen is worth more as a FCEV fuel than as a source of electricity. For example, with the base case long-term hydrogen system, hydrogen can be sold at $5.11/kg, which is equivalent to gasoline selling at $2.17/gallon if used in a conventional car[24]. The EIA is projecting that the average gasoline price in 2015 will be $3.81/gallon. In the model, we assume that 50% of all cars are hybrid electric vehicles (HEVs), and hydrogen is priced such that the FCEV owner will pay the same cost per mile as the average gasoline vehicle owner (50/50 split between HEVs and ICVs.) The revenue from selling hydrogen as a fuel then reduces the necessary price of stored electricity in order for the hydrogen storage system owner to make a 10% real, after-tax return on investment in addition to paying all hydrogen storage system operating costs. We assume that the storage facility sells 1,530 kg/year[25] of hydrogen fuel[26]. This corresponds to the hydrogen demand of a mature hydrogen fueling station that fuels 300 cars/day, a modern high-volume fueling station.

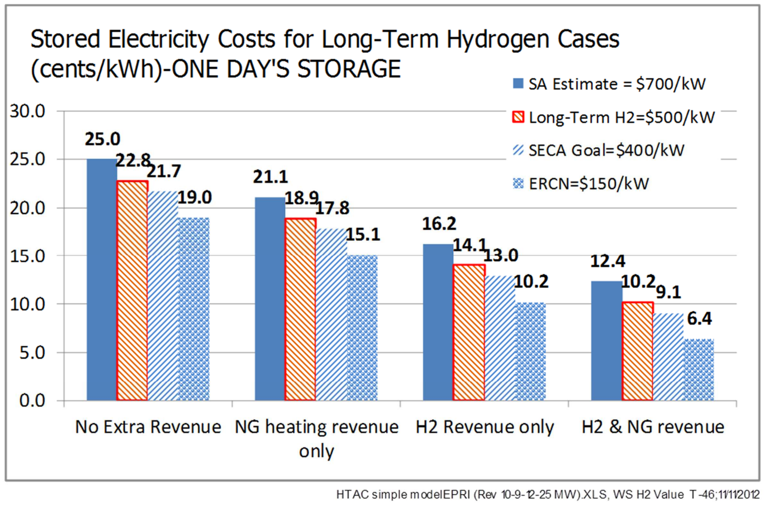


Figure 17. Required cost of on-peak electricity for one day's storage for CHHP systems to yield a 10% real, after-tax return on investment

Revenue from displaced heating fuel

The storage system owner can also reduce costs of heating (or cooling) by using the waste heat from a SOFC to offset natural gas otherwise purchased to heat the facility. In the model we use the EIA's average projected cost of natural gas in 2015 at $6.29/MBTU[27]; we assume that the waste heat from the SOFC is equivalent to 30% of the HHV of the hydrogen input to the fuel cell, so the total efficiency of the SOFC is 85% (55% electrical efficiency plus 30% heat recovery).

The impact on required electricity peak prices of the hydrogen fuel and displaced natural gas revenue streams is summarized in Figure 17 for the four long-term hydrogen scenarios described above with one day's storage. Required electricity prices can be reduced by selling hydrogen fuel and displacing natural gas heating fuel as shown. For the $150/kW SOFC system, a stored electricity on-peak price of 6.4

[24] This assumes that the FCEV has 2.4 times higher efficiency than a gasoline ICV. -
[25] This value assumes that each FCEV travels 13,000 miles per year with a fuel economy of 68.3 miles/kg, and that - the FCEV owner refuels once every 8 days. -
[26] Initially, if there are too few FCEVs to consume this much hydrogen, it could be sold for other industrial uses, or - the hydrogen could be used for fuel cell fork lift trucks at warehouses and production plants. -
[27] The EIA estimates that residential NG will cost $10.56/Kscf; commercial NG at $8.82/Kscf; and Industrial NG at - $5/Kscf in 2015, and a weighted sales average of $6.60/Kscf. Assuming that NG has a heating value of 1.05 - MBTU/Kscf, this translates into a weighted average NG price of $6.29/MBTU. -

₵/kWh would be sufficient to pay for all operating expenses plus earning a 10% real, after-tax ROI on the original hydrogen storage system capital equipment. For the more probable SOFC costs ($400/kW to $700/kW), the on-peak required prices are still quite promising: 9.1 to 12.4 cents/kWh including both hydrogen fuel sales and the 30% heat recovery to offset natural gas.

The required stored electricity on-peak prices to earn the 10% real, after-tax ROI are shown in Figure 18 for one day's underground storage for the hydrogen and other storage systems. We have added the hydrogen sales revenue and heat recovery to the hydrogen storage long-term case which reduces the required electricity price from 31.5 ₵/kWh to 10.2 ₵/kWh, which is less than the price from a Zn/air storage system, the lowest future battery price at 27.9 ₵/kWh.

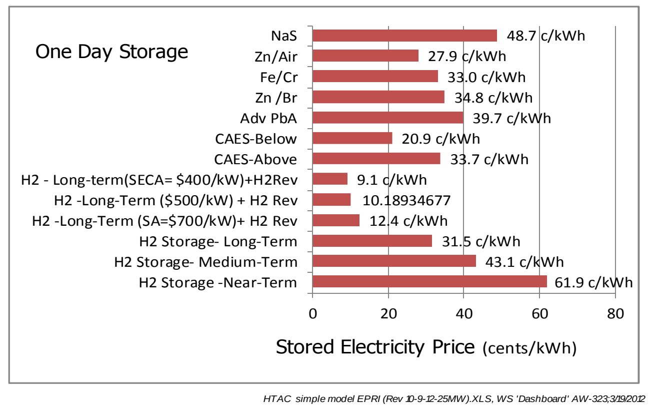


Figure 18. Required on-peak electricity prices for a 10% ROI for one day's storage.

The long-term SOFC systems reduce the required stored electricity prices even further, where we have assumed both hydrogen fuel revenue and displaced natural gas credits for waste heat recovery from these high-temperature fuel cell systems. The SOFC electricity cost estimates of 9.1 to 12.4₵/kWh are quite promising, especially since this electricity is from storage and can be sold at any time of day or year during peak demand.

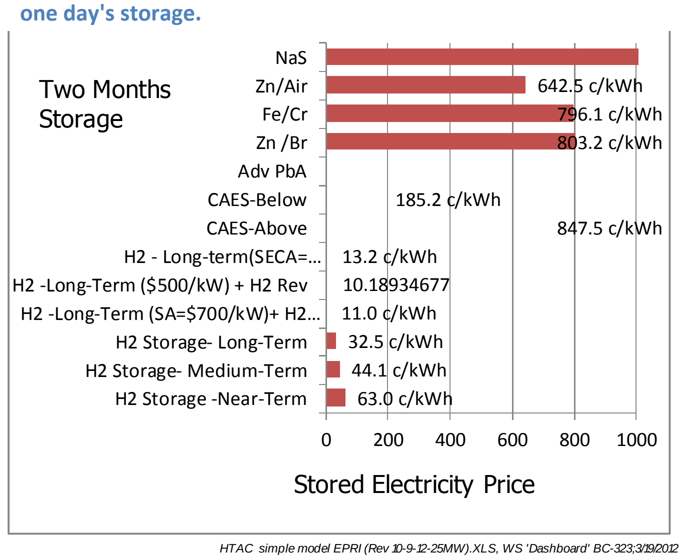


Figure 19. Required electricity prices for two months' storage with the same conditions as Figure 18

The required electricity prices for 2-months storage are shown in Figure 19. With this longer-term storage, all hydrogen storage systems are lower cost than any of the battery or CAES options by large margins. Even the near-term hydrogen storage option is 3 times less expensive than the lowest cost alternative, below ground CAES.

Needless to say, 6-months seasonal storage of hydrogen has an even larger advantage over the competition. As shown in Figure 20, the long-term hydrogen price required is 34.5 ₵/kWh without hydrogen fuel revenue[21], which might be competitive for peak utility loads, and the price could be reduced to the range between 11 to 26 ₵/kWh for the SOFC systems with hydrogen fuel revenue and avoided natural gas credits. Figure 20 also includes the case for generating the electricity from stored hydrogen using a NG combustion turbine at a cost of $665kW, which yields a required on-peak electricity price of 17 ₵/kWh to make the target ROI.

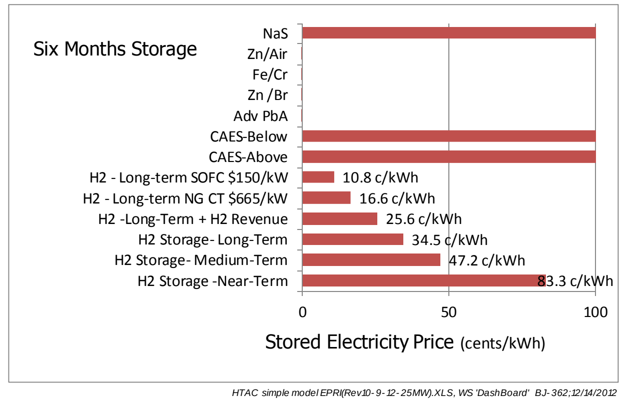


Figure 20. Required electricity prices for a 10% ROI with six months underground storage for hydrogen (all other options are "off the chart!")

Conclusions

Based on our models of energy storage, we come to the following conclusions:

1. - The cost of storing excessive or stranded renewable energy using hydrogen is less expensive than using even advanced battery storage systems such as the Zn/Air advanced battery suggested by EPRI.
2. - Long-term seasonal storage of wind energy is advantageous since winter peak wind energy is sometimes twice the summer wind energy.
3. - For longer-term storage, hydrogen is less expensive than compressed air energy storage (CAES) for storage times longer than 60 days in the near-term, longer than 30 days in the medium-term and longer than 14 days for the long-term hydrogen storage system projections.
4. - If a portion of the stored hydrogen is sold to fuel for fuel cell electric vehicles (FCEVs), and excess thermal energy from a high temperature stationary fuel cell were used to heat or cool buildings, then the stored hydrogen converted to electricity could be sold during peak electricity demand at prices between 9.1 and 12.4 cents/kWh and the project would still make a 10% real, after-tax return on the hydrogen system investment.
5. - With seasonal (6-month) energy storage all other storage options would require peak electricity rates in excess of $1/kWh to make the target 10% ROI.
6. **We conclude that hydrogen energy storage is the only cost effective method of long-term energy storage that could enable the widespread utilization of intermittent renewables such as wind energy.**

Acknowlegements

We would like to thank the members of the HTAC hydrogen enabling renewables working group for their many contributions to this work, including Bob Shaw, Charles Freese, Daryl Wilson, George Sverdrup, Harol Koyama, Jason Marcinkowski, Levi Thompson, Maurice Kaya, Monterey Gardner, Peter Bond, Rob Friedland and Todd Ramsden, with special thanks to Sandy Thomas who constructed the computer model[28] used to provide the data reported in this document and also special thanks to Darlene Steward who developed the community hydrogen storage model and provided NREL data to calibrate the computer model used to generate the data in this report, and a special thanks to Frank Novachek as chairman of the working group for his leadership over several years of bi-weekly conference calls and periodic reports to the full HTAC committee.

Recommendations for Future Work.

While this initial work has demonstrated the value of hydrogen storage to enable greater grid penetration of intermittent renewables, we recommend several additional tasks:

- Determine if there are national policies that would significantly increase renewables penetration
- Conduct systems analyses including and excluding long-term storage using the policy scenarios identified above
- Estimate the value of hydrogen energy storage to the overall system
- Determine what value to assign the otherwise "spilled" renewables to make multi-day scale hydrogen (and other) energy storage economical
- Community Energy Storage/Transportation System: conduct sensitivity analyses to determine what conditions are necessary for a hydrogen system to compete with electric battery system for fueling FCEVs and EVs, respectively, with solar PV energy.
- Model and analyze the economics of "power-to-gas" systems that feed renewable hydrogen into the existing natural gas distribution network, including utilizing that hydrogen for its heating value in current natural gas appliance's, and also analyzing the economics of extracting the hydrogen from the pipeline as fuel for FCEVs.

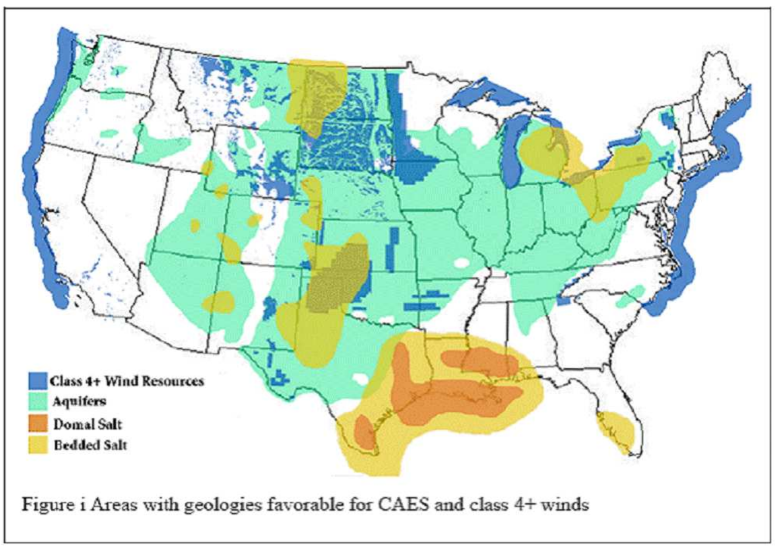


Figure 21.Underground storage potential in the US[29].

- Determine the efficacy of storing hydrogen in underground aquifers and depleted natural gas fields[29],[30]. One source[31] warns that hydrogen can interact with microorganisms and with

[28] Bob Shaw provided the initial guidance and direction for the basic architecture of this computer model.
[29] Some analysts have implied that hydrogen can only be stored in capped salt formations, which would limit underground storage to the Gulf region in the US. For example, according to one source[29] (Figure 21), California does not have any underground aquifers or domed salt caverns.

minerals that can reduce storage volume by plugging micro-porous spaces in the depleted field or aquifer.

---

[30] Source: P. Sullivan, W. short, & N. Blair, NREL, June 2008 "Modeling the Benefits of storage technologies to wind Power." See NREL site for wind storage: http://search.nrel.gov/query.html?qp=site%3Awww.nrel.gov+site%3Asam.nrel.gov&style=nrel&qs=&qc=nrel&ws=0&qm=0&st=1&nh=10&lk=1&rf=0&oq=&col=nrel&qt=wind+energy+storage&x=0&y=0

[31] A. Ozarslan, "Large-scale hydrogen energy storage in salt caverns," *International Journal of Hydrogen Energy*, Vol. 37, Issue 19, Pgs. 14265-14277, October 2012.

Appendix 2

Community Energy: Analysis of Hydrogen Distributed Energy Systems with Photovoltaics for Load Leveling and Vehicle Refueling

Darlene Steward

NREL
NATIONAL RENEWABLE ENERGY LABORATORY






Community Energy: Analysis of Hydrogen Distributed Energy Systems with Photovoltaics for Load Leveling and Vehicle Refueling

Draft September, 2013

Darlene Steward
National Renewable Energy Laboratory

Jarett Zuboy
Contractor

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5600-58205
September 2013

Contract No. DE-AC36-08GO28308

Community Energy: Analysis of Hydrogen Distributed Energy Systems with Photovoltaics for Load Leveling and Vehicle Refueling

Draft September, 2013

Darlene Steward
National Renewable Energy Laboratory

Jarett Zuboy
Contractor

Prepared under Task No. HT12.2030

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

Technical Report
NREL/TP-5600-58205
September 2013

Contract No. DE-AC36-

NATIONAL RENEWABLE ENERGY LABORATORY

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, Colorado 80401
303-275-3000 • www.nrel.gov

Contract No. DE-AC36-

NOTICE

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

Executive Summary

Hydrogen energy storage could complement photovoltaic (PV) electricity generation at the community level. Because PV generation is intermittent, strategies must be implemented to integrate it into the electricity system. Hydrogen and fuel cell technologies offer possible PV-integration strategies, including two community-level approaches analyzed in this report: 1) using hydrogen production, storage, and reconversion to electricity to level PV generation and grid loads; and 2) using hydrogen production and storage to capture peak PV generation and refuel hydrogen-powered vehicles.

These approaches are applied to a community of 100 residences, approximated by the electricity demand of a small hotel in Boulder, Colorado. To assess the impact of increasing PV market penetration, three levels of PV power generation, spanning a broad range in comparison to the community's electricity demand were studied. The simulated community is served by a PV system sized at 1,200 m^2 (producing electricity equivalent to 50% of annual building electricity load), 4,000 m^2 (170%), or 7,000 m^2 (290%).

In the load-leveling system, electricity from the PV panels satisfies building demand directly, and excess PV electricity produces hydrogen via an electrolyzer. A fuel cell converts the hydrogen back into electricity to serve the building demand when PV output is inadequate, and grid electricity satisfies any demand that cannot be met directly by the PV system or stored hydrogen. Seasonal variation in the PV system output has a marked effect on the sizing of the storage systems for the three PV system sizes. For the 1,200 m2 PV system, the PV electrical output exceeds the building load during certain times of the day, but the total daily output never exceeds the total daily load. Therefore, for the 1,200 m2 system, the storage system cycles daily and electricity is never sold back to the grid. In contrast, for the 4,000 and 7,000 m2 systems, the daily PV output often exceeds the daily load, so multi-day storage is needed. For the 4,000 m2 system, 780 kg (~14,600 kWh) equivalent to approximately 9 days of storage accommodates the seasonal variation in PV output and no electricity is sold back to the grid. For the 7,000 m2 system, it is not feasible to fully account for seasonal variation in PV output with storage. Therefore, the storage system for the 7,000 m2 system was sized to approximately 4 days of storage, and a considerable amount of electricity is sold to the grid during periods when the storage system is full.

The vehicle-refueling system is similar to the load-leveling system, except that vehicles use the excess energy instead of buildings, and no electricity is sold back to the grid. The amount of electricity produced in excess of the building load determines the number of vehicles - either hydrogen fuel cell vehicles or plug-in electric vehicles – that could be fueled in each case. The vehicle-refueling methods include electrolytic hydrogen production for hydrogen-powered vehicles and battery storage for plug-in electric vehicles. In the case of vehicle refueling, the storage systems are sized to meet the minimum needed for a complete fill (in the case of the 1,200 m2 PV system) or one day of excess PV output plus 50 percent. It is assumed that vehicle fuel demand that cannot be met by the community refueling system during the winter and stretches of cloudy weather will be accommodated by nearby stations.

The vehicle-refueling cost analysis is performed for two cases: Case 1, in which all PV electricity output in excess of the building load is used for vehicle refueling, and Case 2, in which all PV electricity output before noon is used for vehicle refueling in addition to all PV output in excess of the building load.

Table ES-1 shows the levelized cost of electricity (LCOE) from the storage system for each load-leveling scenario. The systems are sized for load leveling under the constraint of a limited grid/transformer size but are not fully optimized for cost. The results show a relatively complex relationship between PV system size and the economics of power generation from each system. The leftmost set of results show the LCOE of the PV generated electricity that is routed directly to the building plus electricity that is produced from the storage system. Costs tend to increase as the delta between the PV system output and the building load increases because the storage system must be larger. However, this upward trend in cost is balanced by better utilization of the storage equipment (electrolyzer, hydrogen tanks, and fuel cell) for the larger systems. So, the LCOE for electricity is lowest for the small PV system and highest for the mid-range system. The trend in storage system utilization is illustrated by the rightmost set of results, which show the LCOE for only the stored portion of the electricity. In this set of results, the LCOE steadily decreases with increasing PV system size. In all cases, the electricity produced by either the battery or H2 storage system is more expensive than grid electricity. Therefore, the storage system must provide benefits in addition to cost, such as relieving grid congestion and/or providing backup power, to be cost effective.

Table ES-1. Load-Leveling System Costs With and Without PV Costs Included

Scenario	Total Direct Capital Cost Including PV System ($000)	LCOE of All Electricity (Direct Supply to Building + Stored Electricity) (¢/kWh) (% of output to storage)**	Total Direct Capital Cost without PV System ($000)	LCOE of Stored Electricity (¢/kWh)**
1,200 m^2 PV/storage system	$727	33 (32%)	$271	109
4,000 m^2 PV/storage system	$2,958	57 (70%)	$1,438	62
7,000 m^2 PV/storage system*	$3,393	45 (38%)	$733	36

*The 7,000 m^2 PV system produces close to 3 times the building load. Therefore, nearly the entire building load can be supplied with the PV system direct output plus stored electricity. After supplying the building load, a large fraction of the PV system output (44%) is sold to the grid at the cost of producing it.
** Levelized costs include all direct and indirect costs for the apportioned cost of the PV system, hydrogen/battery production, storage and delivery, and replacement and operating expenses over the life of the system.

The vehicle-refueling analysis shows the potential for community-level hydrogen refueling using only renewably generated electricity (Table ES-2). With the 4,000 m^2 PV system, the number of fuel cell vehicles served (70–80) roughly matches the modeled community size (100 households). The levelized hydrogen cost ranges from \$34/kg (\$1.01/kWh) for the 1,200 m^2 Case 1 system to \$11/kg (\$0.34/kWh) for the 7,000 m^2 Case 2 system. The cost of battery storage of electricity for electric vehicles ranges from \$0.57/kWh–\$0.39/kWh, also decreasing with increasing system size. The levelized cost of hydrogen is high for even the most favorable case in comparison to expected early commercial station hydrogen costs. However, the system produces 100% renewable hydrogen and provides potentially valuable load leveling of distributed PV output allowing for grid integration of much larger PV systems. The hydrogen system cost reduction for the larger systems is due, as for the load leveling system, to better utilization of the equipment. The hydrogen system configuration is also more flexible than the battery system because there are more independent pieces of equipment. For small systems, this is a disadvantage, but for larger systems the increased flexibility reduces costs because an incremental increase in hydrogen storage capacity per kWh (hydrogen tank) is less expensive than an incremental (per kWh) increase in electrochemical storage. Even though the hydrogen system is lower cost than the battery system for the largest storage case, the electric vehicle is less expensive on a fuel ¢/mile basis because of its higher efficiency in comparison to the fuel cell vehicle.

For both the load leveling and vehicle fueling scenarios, the system cost is highly dependent on component costs and system configuration. In all scenarios, the load-leveling or refueling system reduces peaks and valleys in grid demand and energy fed onto the grid. The vehicle refueling scenarios provide as much smoothing of the PV system output/grid demand as the load-leveling scenarios. Storage and/or diversion of excess electricity from distributed generation systems that can smooth seasonal and daily variations in PV system output may be advantageous for very high levels of PV penetration.

Table ES-2. Summary of Vehicle Refueling Cost Results

Hydrogen for Fuel Cell Vehicles*								
	Case 1 (Excess Electricity)				Case 2 (Excess Electricity + Morning Output)			
PV Size (m^2)	Production (kg H_2/yr)	Vehicles Served	H_2 LCOE ($/kg)	H_2 Cost (¢/mi)	Production (kg H_2/yr)	Vehicles Served	H_2 LCOE ($/kg)	H_2 Cost (¢/mi)
1,200	1,804	9	34	56	3,541	17	22	38
4,000	14,564	72	13	22	16,985	84	12	21
7,000	29,274	146	12	20	31,898	159	11	19
Electricity for Battery-Electric Vehicles*								
	Case 1 (Excess Electricity)				Case 2 (Excess Electricity + Morning Output)			
PV Size (m^2)	Production (kWh/yr)	Vehicles Served	Elec. LCOE ($/kWh)	Elec. Cost (¢/mi)	Production (kWh/yr)	Vehicles Served	Elec. LCOE ($/kWh)	Elec. Cost (¢/mi)
1,200	61,726	17	0.57	17	121,936	35	0.45	13
4,000	500,755	143	0.41	12	585,475	168	0.40	12
7,000	1,008,212	289	0.39	11	1,100,877	316	0.39	11

* Levelized costs include all direct and indirect costs for the apportioned cost of the PV system, hydrogen/battery production, storage and delivery, and replacement and operating expenses over the life of the system. For the 4,000 and 7,000 m^2 PV systems, the hydrogen capital costs are lower than the battery-electric capital costs; however, the higher efficiency of the battery-electric vehicle system (29 kWh/100 miles for EVs versus 55.6 kWh/100 miles for FCEVs[1]) still results in a lower per-mile cost for the battery-electric vehicle system.

[1] FuelEconomy.gov accessed 6/20/2013.

Table of Contents

1 Introduction

Higher penetrations of distributed renewable energy systems, specifically residential rooftop PV systems, could affect loading and capacity margins for community-level electricity distribution systems. PV output typically peaks slightly before the peak daily electricity demand. This offset could cause overloading of local distribution equipment at high PV penetration levels. The addition of plug-in electric vehicles, which would primarily be charged at residences, might also affect loading of distribution systems. Several researchers have analyzed the effect of electric and plug-in hybrid electric vehicles on the grid (Denholm, Kuss et al. ; Srivastava, Annabathina et al. 2010). Denholm analyzed options for integrating PV and electric vehicle charging, finding benefits of mid-day vehicle charging for reduction of petroleum use and potentially enabling smaller vehicle batteries. While Denholm's analysis focused on mid-day charging at commercial places of business, this analysis addresses the unique challenges of integrating large penetrations of PV at the residential level where grid capacity constraints may be most acute.

Hydrogen energy storage could complement photovoltaic (PV) electricity generation at the community level. Because PV generation is intermittent, strategies must be implemented to integrate it into the electricity system. Hydrogen and fuel cell technologies offer possible PV-integration strategies, including two community-level approaches discussed in this paper: 1) using hydrogen production, storage, and reconversion to electricity to level PV generation and grid loads; and 2) using hydrogen production and storage to capture peak PV generation and fuel hydrogen-powered vehicles.

Energy storage is one potential strategy for addressing load variations due to high residential PV penetration. This brief study analyzes the costs and benefits of installing hydrogen-based energy storage for community-level PV system load leveling. It examines the effects of increasing PV penetration in residential neighborhoods on the use of grid electricity and the opportunity for hydrogen energy storage.

Peak PV output could also be diverted for use directly in electric vehicles or, after conversion to hydrogen, in hydrogen-powered fuel cell vehicles. In this analysis, the electricity or hydrogen is temporarily stored in batteries or hydrogen tanks so that vehicles can be refueled when the residents return home in the evening.

The target scenario for the study is approximately 100 single-family, detached houses served by a single pad-mounted transformer at the end of a grid distribution line. As PV penetration increases for these houses, what are the opportunities and economics for energy storage using hydrogen? How does that compare to diverting the excess electricity to fueling of vehicles? A modified version of the U.S. Department of Energy's Fuel Cell Power Model (FCPower 2012) was used to perform this analysis.

The next section describes the building profile and PV systems followed by the load-leveling and vehicle-refueling systems. Section 3 shows cost analysis results for the load-leveling and vehicle-refueling systems, and Section 4 offers conclusions and suggestions for future work.

2 System Descriptions and Energy Flows

The following subsections detail the characteristics of the building profile used in both the load-leveling and vehicle-refueling scenarios; the electrolyzer, fuel cell, and PV systems used in the scenarios; and the load-leveling and vehicle refueling systems themselves.

2.1 Building Profile and PV Systems

The same building profile was used for the load-leveling and vehicle-refueling scenarios. The hourly load profile for a small hotel in Boulder, Colorado was used as a surrogate for a community of 100 residences (Field et al. 2010; NREL 2009). The hotel load profile is expected to be similar to the load profile for a residence because of similar use patterns; most people get up and ready for work in the morning and then return later in the afternoon. This use pattern results in a peak in electricity demand between 6:00 and 10:00 a.m. and another between 5:00 and 10:00 p.m. Because the hotel load, with an average demand of about 65 kW, is larger than would be expected for 10–15 single family residences (with an average demand of 1–2 kW per household), the analysis was scaled up in size. However, the equipment costs are scaled linearly, and the energy flow relationships are the same as for a smaller system. Some characteristics of the hotel building load profile are listed in Table 1. Figure 1 plots the electricity demand for the hotel during a typical day in July.

Table 1. Key Characteristics of the Boulder Hotel Building Load Profile

Building Load Statistics	
Demand maximum (kW)	125.3
Demand minimum (kW)	28.4
Demand average (kW)	65.4
Demand Stdev (kW)	22.8
Demand total (kWh/year)	572,518

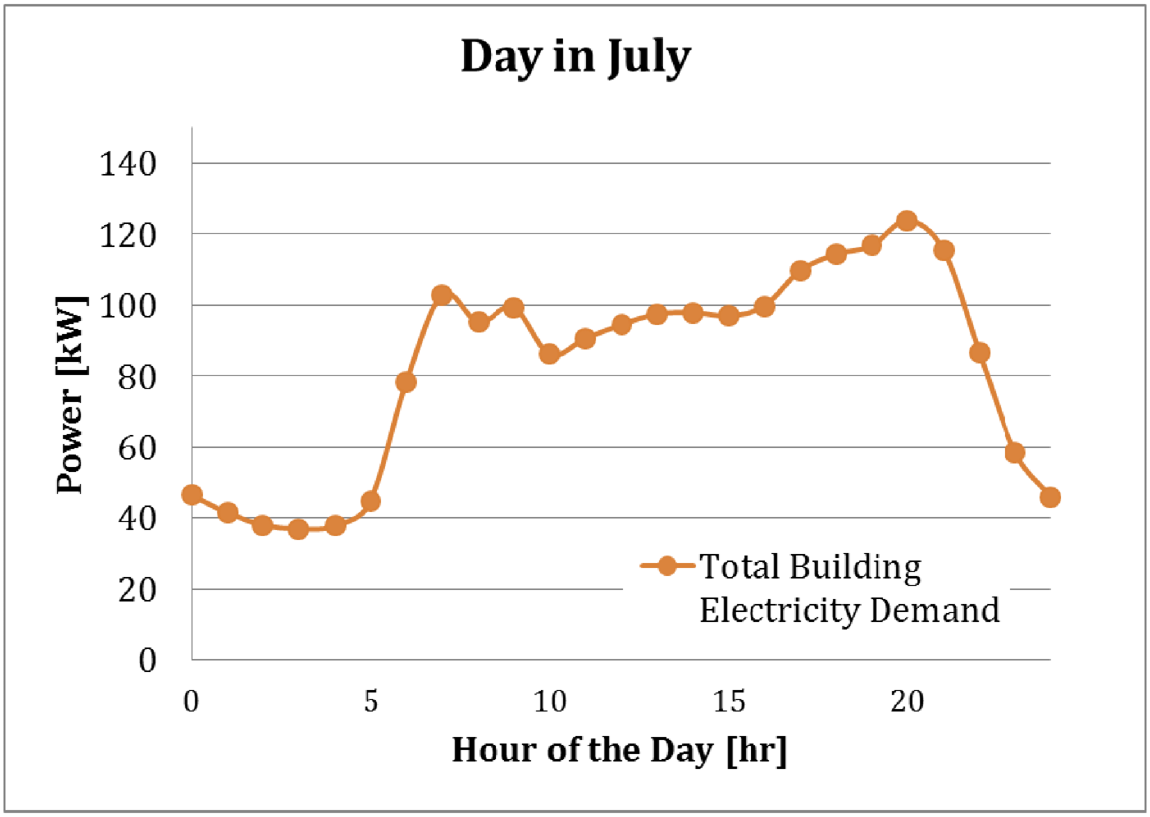


Figure 1. Building electricity demand profile, selected day in July

The same PV systems were used for the load-leveling and vehicle-refueling scenarios (Table 2). The three PV systems range in size from about half the yearly building load to almost three times the building load. The capacity factor for the PV systems is 18%.[2] NREL's solar hourly solar resource data for Boulder, Colorado (NREL 2009) was imported into the FCPower model for use in the simulations.

Table 2. Key PV System Performance Parameters

PV System Size (m^2)	Peak Rated Output (kW)	Yearly Output (kWh)	Approximate Percent of Building Load
1,200	183	286,704	50%
4,000	611	955,681	170%
7,000	1,069	1,672,442	290%

2.2 Load-Leveling System

Figure 2 shows a schematic representation of the equipment and building layout for the load-leveling system. Electricity from the PV panels is first used to satisfy the building demand (100 houses approximated by the hotel profile described previously) directly. If the output from the

[2] The capacity factor is calculated as the actual PV output (kWh) divided by the potential output if the PV panels were producing at their maximum power for 24 hours a day.

PV system is higher than the building demand at that time, the electricity is routed to the electrolyzer where it is used to produce hydrogen for storage. During periods when the demand is high but PV output is low, for example in the evening, the stored hydrogen is used in the fuel cell to produce electricity for the building demand. Any additional building demand is met using electricity from the grid. On rare occasions, the storage system may be full and excess electricity from the PV system is routed to the transformer and fed onto the grid. In this scenario, the fuel cell output is only used to satisfy the building demand and is never routed to the grid.

Seasonal variation in the PV system output has a marked effect on the sizing of the storage systems for the three PV system sizes. Seasonal fluctuations in PV output/H_2 produced by the Electrolysis system can be accommodated for the 1,200 and 4,000 m^2 systems. However, sizing of the hydrogen production and storage system to accommodate seasonal variations in hydrogen production for the 7,000 m^2 PV system is not practical. Therefore, for the 7,000 m^2 system, both the electrolyzer and hydrogen storage system are scaled down and more electricity is routed to the grid.

For the 1,200 m2 PV system, the PV electrical output exceeds the building load during certain times of the day, but the total daily output never exceeds the total daily load. Therefore, for the 1,200 m2 system, the storage system cycles daily and electricity is never sold back to the grid. In contrast, for the 4,000 and 7,000 m2 systems, the daily PV output often exceeds the daily load, so multi-day storage is needed. For the 4,000 m2 system, 780 kg (~14,600 kWh) equivalent to approximately 9 days of storage accommodates the seasonal variation in PV output and no electricity is sold back to the grid. For the 7,000 m2 system, it is not feasible to fully account for seasonal variation in PV output with storage. Therefore, the storage system for the 7,000 m2 system was sized to approximately 4 days of storage, and a considerable amount of electricity is sold to the grid during periods when the storage system is full.

Table 3 shows the efficiencies of the electrolyzer, fuel cell, and compressor modeled in the system.

Table 3. Efficiencies of the Load-Leveling System's Electrolyzer, Fuel Cell, and Compressor

Model Parameter	Units	Value
Electrolyzer efficiency	%HHV	78%–87%[a]
Fuel cell efficiency	%LHV	53%–58%[b]
Compressor system efficiency	%HHV	92%

[a] 66%–74% LHV. Electrolyzer efficiency decreases with increasing hydrogen output. The electrolyzers for the 1,200 and 4,000 m^2 systems operate, on average, at about 40% of their rated power. The electrolyzer for the 7,000 m^2 system operates at about 84% of its rated power.

[b] Fuel cell efficiency decreases with increasing electricity output. For the three systems, the fuel cell capacity factor ranges from 89% (1,200 m^2 system) to 45% (7,000 m^2 system).

Figure 3 shows the energy flows for this system (with 1,200 m^2 of PV) during a day in October. On this day, there is sufficient PV generation to carry the load without using the grid and produce hydrogen for storage (purple "X"s) from about 10:00 a.m. to 5:00 p.m. Sufficient hydrogen is stored during the day to carry part of the load in the evening; however, no hydrogen remains to produce electricity during the early morning hours. As Figure 4 shows, for the scenario with 1,200 m^2 of PV, there is a wide variation in the amount of hydrogen produced during various times of the year. During periods of high demand (e.g., the day in July) or low solar output (e.g., the day in January), very little hydrogen is produced.

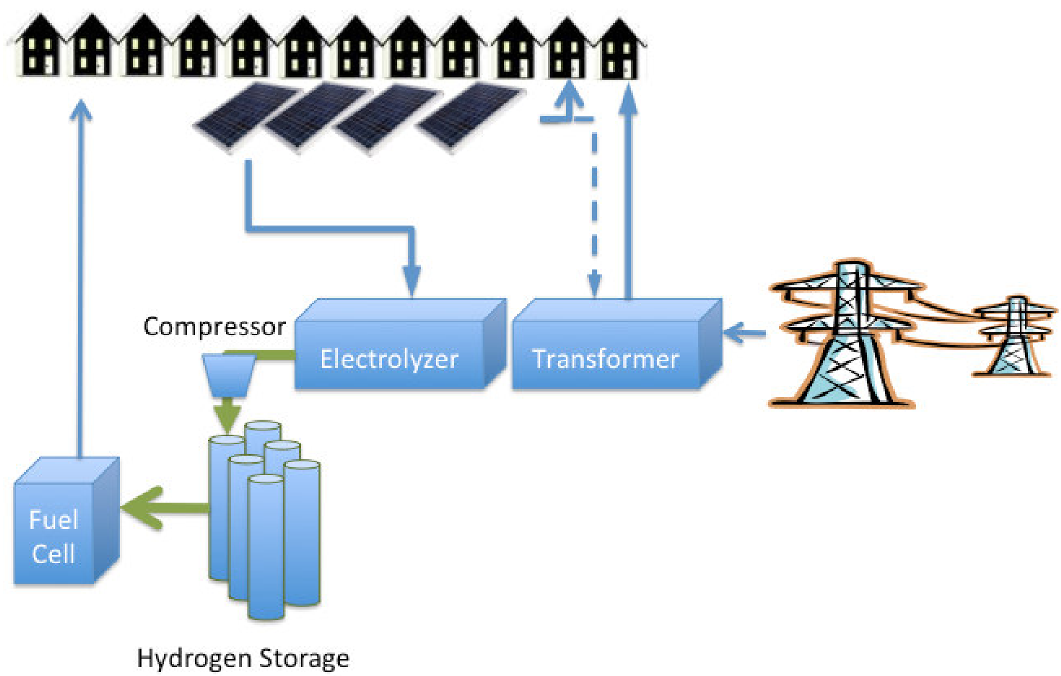


Figure 2. Schematic diagram of equipment and energy flows for the load-leveling system

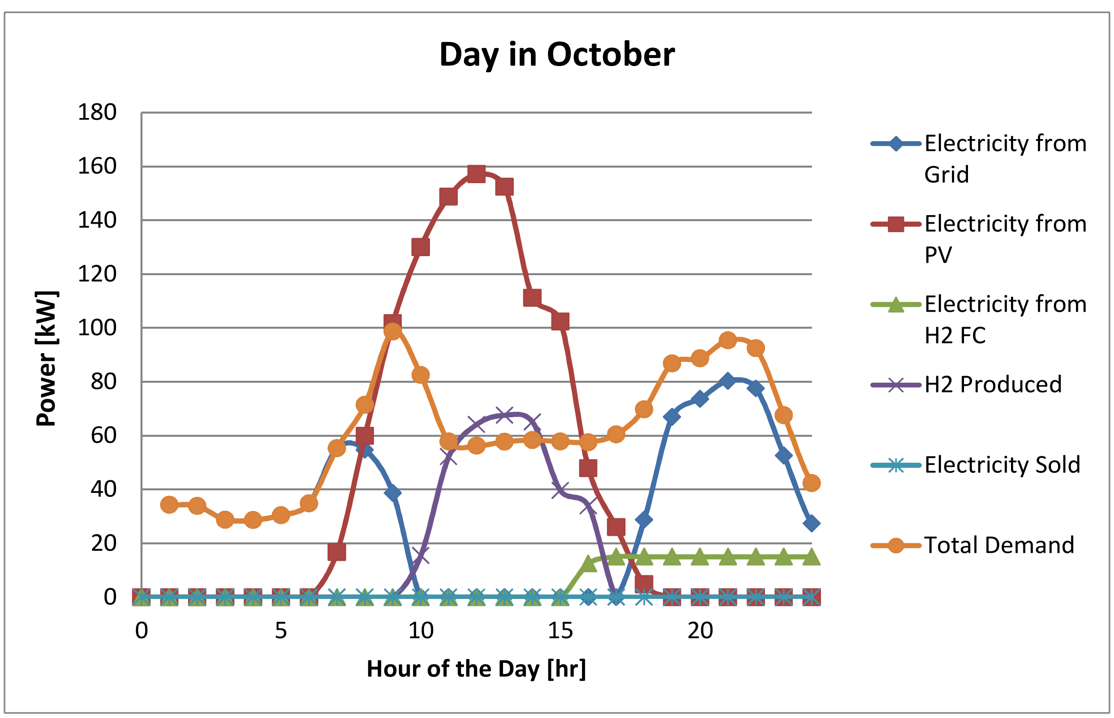


Figure 3. Boulder hotel electricity demand, PV generation, and storage system energy flows for a typical day in October (1,200 m^2 PV)

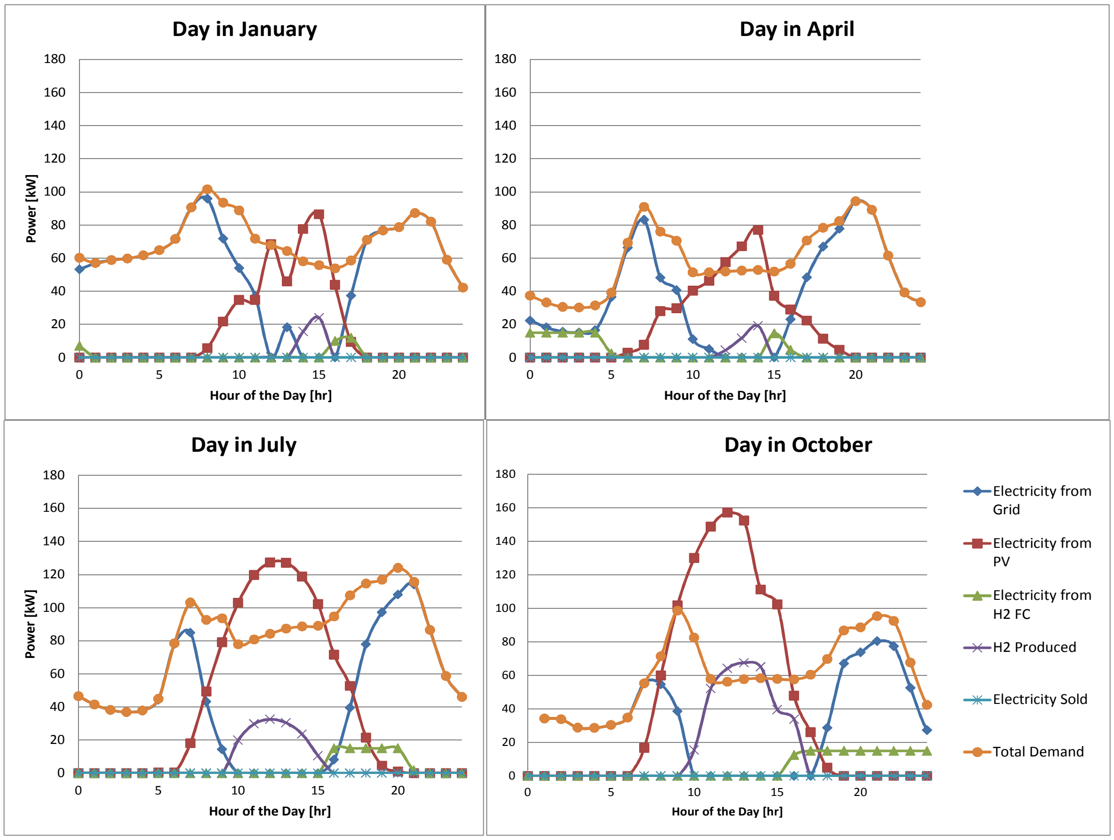


Figure 4. Seasonal variation with 1,200 m^2 of PV, four selected days

With 1,200 m^2 of PV installed, there is insufficient hydrogen production/storage to completely offset AM and PM peak power draws from the grid, especially during the summer when demand is higher. However, peak draws from the grid are reduced 10%–15% in the afternoon and evening peak period for part of the year. The peak output from the PV system is usually between 120 and 160 kW, which typically occurs when the building load is around the average of 65 kW. Without the storage system, the transformer occasionally would need to accommodate the difference in output of up to 100 kW of electricity being fed onto the grid. The storage system completely eliminates this energy flow. Table 4 summarizes the energy flows for the 1,200 m^2 PV/energy storage system. Figure 5 and Figure 6 show energy flows on various days for the 4,000 and 7,000 m^2 PV systems.

Table 4. Summary of Energy Flows for 1,200 m^2 PV/Energy Storage System

Equipment/System	System Size	Yearly Output	Capacity Factor (% of Max Output during Operation, [h/yr])	Percent of Building Load (Building + Compressor)
PV system	1,200 m^2 (~ 183 kW peak rated output)	286,704 kWh	18	50 (total) 34 (direct supply)
Electrolyzer	127 kW input	1,833 kg	38 [1,904]	—
Hydrogen storage	16 kg	~ 1 cycle per day	—	—
Hydrogen fuel cell	15 kW output	32,094 kWh	89 [2,402]	6
Grid	—	348,771 kWh	—	61
Electricity sold	—	0 kWh	—	—

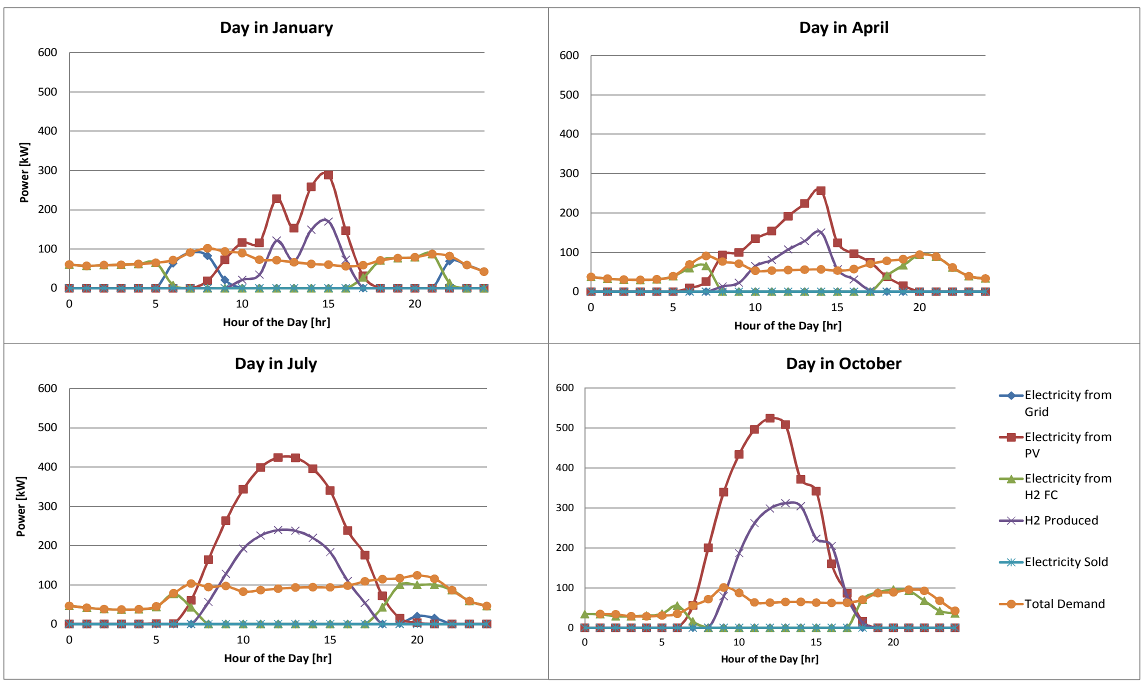


Figure 5. Seasonal variation with 4,000 m^2 of PV (see Figure 3 for the key)

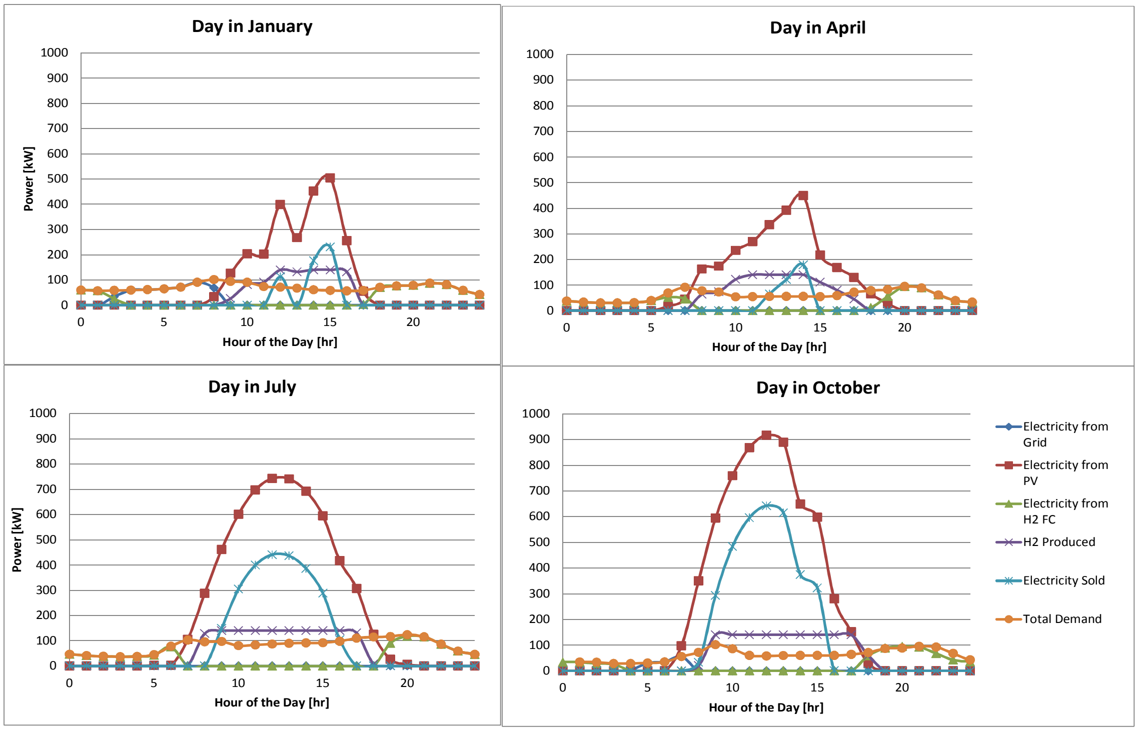


Figure 6. Seasonal variation with 7,000 m^2 of PV (see Figure 3 for the key)

Table 5 summarizes the energy flows for the 4,000 m^2 system. The total yearly PV output is 167% of the building yearly load. However, only about 48% of the PV output occurs at times when it can directly supply the building load. For this configuration, there is insufficient hydrogen production/storage to offset AM and PM peak power draws from the grid completely, especially during the summer when demand is higher. However, peak draws from the grid are reduced 50%–75% in the afternoon and evening peak period for most of the year.

Table 5. Summary of energy flows for 4,000 m^2 PV system

Equipment/System	System Size	Yearly Output	Capacity Factor (% of Max Output during Operation, [h/yr])	Percent of Building Load (Building + Compressor)
PV system	4,000 m^2 (~ 611 kW peak rated output)	955,681 kWh	18	167 (total) 48 (direct supply)
Electrolyzer	578 kW input	14,797 kg	39 [3,265]	—
Hydrogen storage	780 kg	Variable days of storage depending on the season	—	—
Hydrogen fuel cell	100 kW output	277,770 kWh	55 [5,065]	47
Grid	—	25,995 kWh	—	4
Electricity sold	—	0 kWh	—	—

Table 6 summarizes the energy flows for the 7,000 m^2 system. The total yearly PV output is 292% of the building yearly load. However, only about 51% of the building load can be supplied by the PV system directly. In this scenario, there is sufficient hydrogen production and storage capacity to supply 42% of the building load using the hydrogen fuel cell. The hydrogen fuel cell for the 7,000 m^2 system supplies less of the building load than the fuel cell for the 4,000 m^2 system because storage for the 7,000 m^2 system is smaller than for the 4,000 m^2 system and thus provides less seasonal storage than for the 4,000 m^2 system. The peak output from the PV system is about 1,069 kW, which typically occurs when the building load is 60–100 kW. Without the storage system, the transformer would need to accommodate the difference in output of close to 1,000 kW of electricity being fed onto the grid. The storage system reduces this energy flow by diverting some of the excess electricity to the electrolyzer. In the configuration analyzed, the electrolyzer reduces peak electricity flow to the grid by 220 kW, the input electricity capacity of the electrolyzer. For the 7,000 m^2 PV system scenario, not all peaks in energy flow to the grid are eliminated. In this scenario, there are several occasions when the energy flow to the grid exceeds 700 kW.

Table 6. Summary of Energy Flows for 7,000 m^2 PV System

Equipment/System	System Size	Yearly Output	Capacity Factor (% of Max Output during Operation, [h/yr])	Percent of Building Load (Building + Compressor)
PV system	7,000 m^2 (~ 1,069 kW peak rated output)	1,672,442 kWh	18	292 (total) 51 (direct supply)
Electrolyzer	221 kW input	12,757 kg	84 [3,619]	—
Hydrogen storage	325 kg	Variable days of storage depending on the season	—	—
Hydrogen fuel cell	125 kW output	246,321 kWh	45 [4,388]	42
Grid	—	38,405 kWh	—	7
Electricity sold	—	729,410 kWh	—	44% of PV output

2.3 Vehicle-Refueling System

The vehicle-refueling system is similar to the load-leveling system, except that vehicles absorb the excess energy instead of buildings, and no electricity is sold back to the grid. The vehicle refueling serves the purpose of load leveling, eliminating large electricity fluctuations and reverse power flow from the PV system through the transformer. The modeled community consists of about 100 houses (approximated with the hotel profile described previously) with corresponding vehicle-refueling demand. Electricity from the PV system supplies the building load; when PV output is less than the building load, the grid supplies the difference. The transformer and distribution lines have enough capacity to supply the peak building load. Figure 7 shows a schematic of the system.

The PV system also produces all fuel for the vehicles (i.e., the grid does not supply electricity for vehicle fuel). Two types of vehicle refueling systems are compared in this analysis. One uses electrolytic hydrogen production for hydrogen-powered vehicles (Figure 8), and the other uses battery storage for charging of plug-in electric vehicles (Figure 9).

The vehicle-refueling cost analysis was performed for two cases:

- Case 1—All PV electricity output in excess of the building load is used for vehicle refueling.
- Case 2—All PV electricity output before noon is used for vehicle refueling in addition to all PV output in excess of the building load.

Figure 10 show schematics of the PV electricity output used for vehicle refueling in Case 1 and Case 2.

In the hydrogen vehicle-refueling analysis, an electrolyzer is sized to accommodate the maximum electricity production used to generate hydrogen.[3] The compressor is sized to the peak hourly hydrogen flow rate. The storage system is assumed to cycle fully each day (i.e., there is no multi-day storage). The amount of hydrogen storage needed was calculated by running the model with very large daily hydrogen demand to ensure that the analysis simulates daily cycling of the storage system. The storage volume needed was then set at the maximum amount of hydrogen in storage at any time during the year (for the very high demand case) plus 50% or a minimum value for a full tank refueling based on the assumed cascade system volume of 65 kg. This results in about 75 kg of storage for the smallest system (1,200 m^2 PV Case 1), which produces only an average of approximately 5 kg/day. A relatively large excess storage was assumed for the larger systems to account for the large daily fluctuations in PV output and the fact that actual hydrogen refueling is likely to be less uniform than modeled. The analysis does not assume that the additional storage accounts for seasonal variations in hydrogen/electricity demand or production. Month to month variations in production are not large; the average monthly hydrogen production for the 4,000 m^2 system is ~1,200 kg/month with a standard deviation of ~140 kg/month. However, the high and low production months (March and December respectively) only roughly correspond to expected high and low demand months (June-August and November-January respectively) so in reality, it might be necessary to refuel vehicles offsite occasionally during part of the summer. There is also a predictable dip in PV output during the hottest part of the summer, when fuel demand is expected to peak. Although the analysis did not explicitly address seasonal variations in production or demand, it is likely that the additional storage modeled would be sufficient to accommodate them.

One 350-bar hydrogen dispenser with two hoses is used for daily hydrogen production ranging from only about 5 kg/day for the 1,200 m^2 Case 1 system to about 90 kg/day for the 7,000 m^2 Case 2 system. It is expected that hydrogen fuel cell vehicles used primarily for commuting would be refueled about once per week. Although most vehicle manufacturers are planning for 700 bar refueling, 350-bar dispensing is assumed for this analysis. Vehicles designed for the higher pressure are capable of being refueled at lower pressure (although the tank cannot be completely filled) and 700 bar dispensers are considerably more complex and expensive than

[3] In this analysis, the maximum electricity production used to generate hydrogen is calculated for two cases: In Case 1, it is the difference between the PV output and the building load, and in Case 2 it is the amount in Case 1 plus all PV electricity generated before noon.

350 bar dispensers. The additional expense was not felt to be justified for the low throughput of hydrogen and community-based refueling envisioned in this study.

The alternative vehicle-refueling system uses electricity to charge a zinc-air storage battery system consisting of one or more batteries that may be located together or distributed through the community. The batteries are used to store energy for a brief period (less than 1 day) so that battery-electric vehicles can be charged in the evening and overnight. The battery system is sized to accommodate the maximum difference between the PV daily output (kWh) and the building load plus 50% in order to have enough capacity for charging of several vehicles (for the smaller system cases) and to more closely match the hydrogen systems. The battery system is assumed to discharge fully each day (i.e., there is no multi-day storage), and each vehicle is refueled with a home-based Level 1 (120V) charging unit (comparable to a 350-bar hydrogen system). The zinc-air battery/vehicle charging system is assumed to have an overall electrical efficiency of 73%.[4] The purpose of modeling this battery-electric system is to provide a reasonable contrast with the hydrogen-fuel cell system, rather than to model a real-world battery-electric system in detail.

The hydrogen and electric vehicles are assumed to have identical charging profiles every day of the year, and all vehicles are refueled between 4:00 and 9:00 p.m. Although this is a more realistic profile for hydrogen refueling than for electric vehicle nighttime charging, the differences in profiles do not affect the analysis because neither type of vehicle would be refueled at a time when a significant amount of PV electricity could be used directly for vehicle fueling. In all cases, the amount of fuel produced is determined by how much of the PV output can be directed to the battery or electrolyzer. Therefore, the same amount of electricity is used for vehicle refueling whether the vehicles are powered by hydrogen or electricity; the battery-electric system simply powers more vehicles because of its higher efficiency.[5] Figure 11 shows the vehicular hydrogen/electricity demand profile along with the building electricity demand profile. Figure 12 shows all the system energy flows. Table 7 and Table 8 show the energy flows for Cases 1 and 2.

[4] Zinc-air battery round trip efficiency was assumed to be slightly less than the value reported by Rastler to account for losses in home charging of vehicles.
[5] The all-electric vehicles are based on the Nissan Leaf with a 100-mile all-electric range and driven 12,000 miles per year.

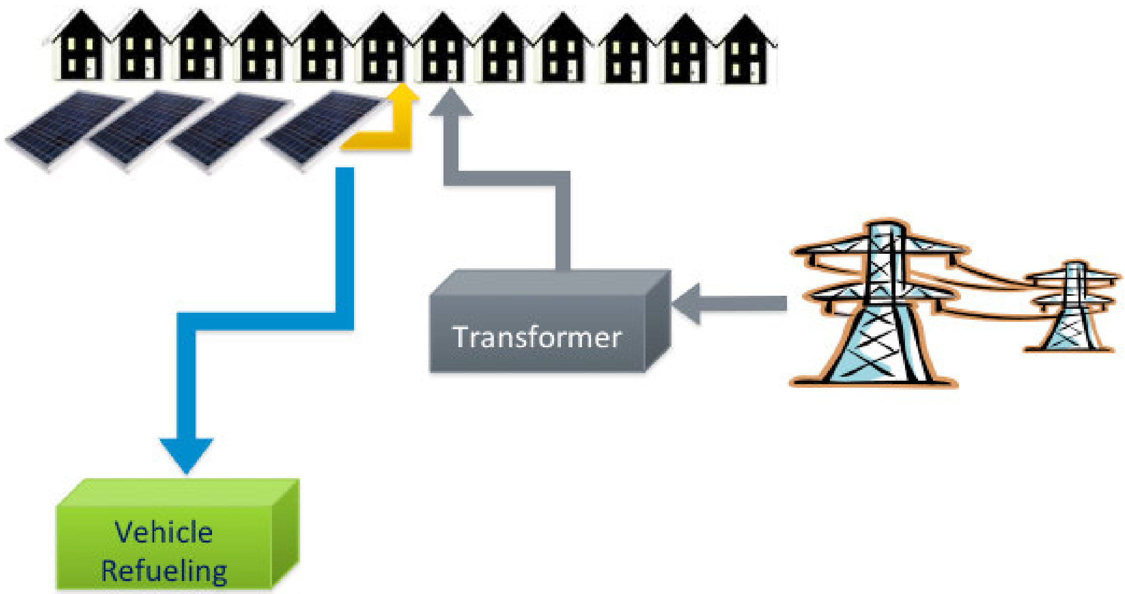


Figure 7. Schematic diagram of equipment and energy flows for the vehicle-refueling system. There is no energy flow from the vehicle-refueling system to the building.

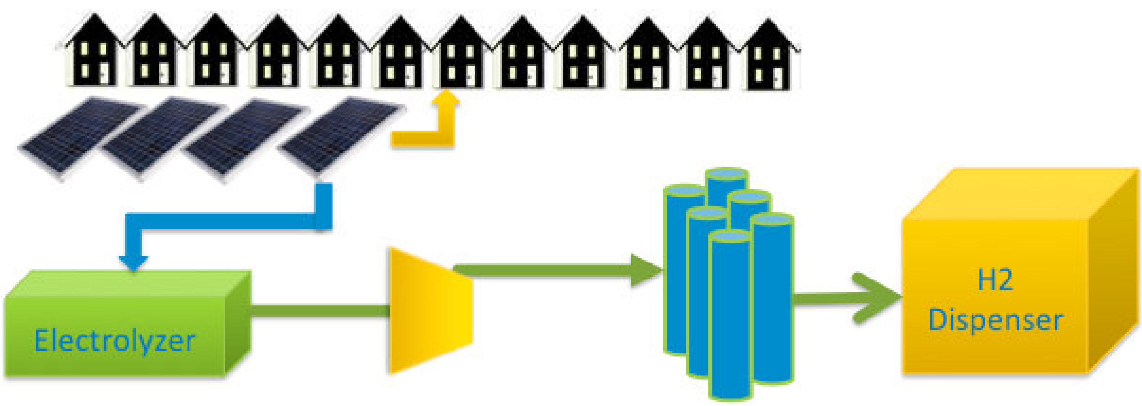


Figure 8. Detail of hydrogen vehicle-refueling configuration. There is no energy flow from the vehicle-refueling system to the building.

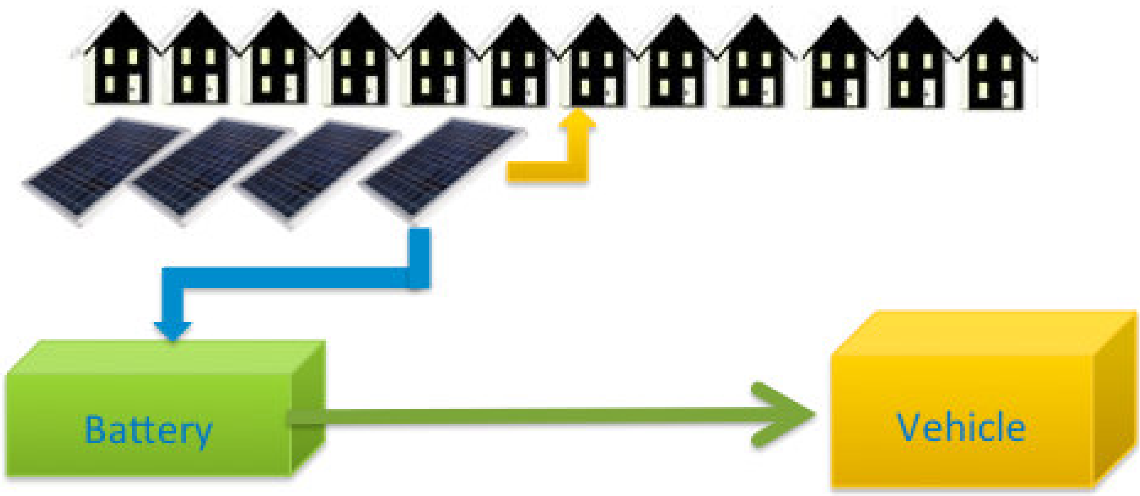


Figure 9. Detail of alternative (battery) vehicle-refueling configuration. There is no energy flow from the vehicle-refueling system to the building.

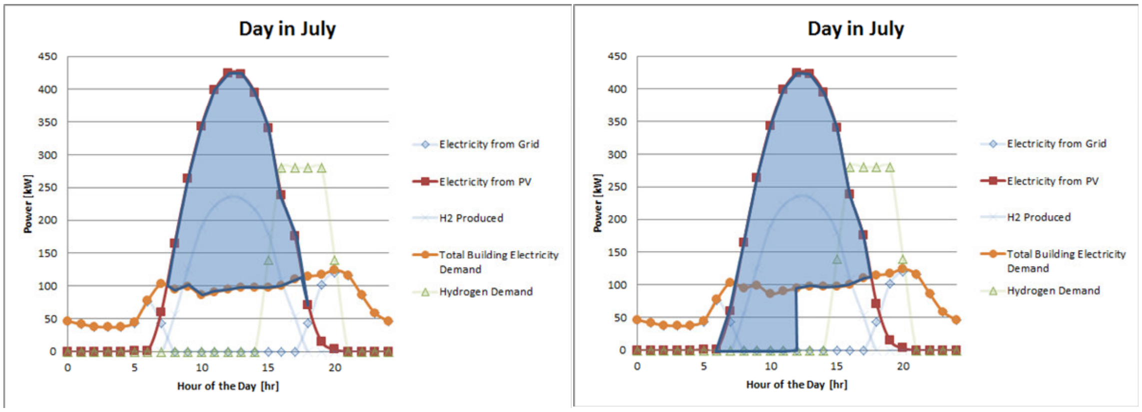


Figure 10. PV electricity output used for vehicle refueling in Case 1 (left) and Case 2 (right)

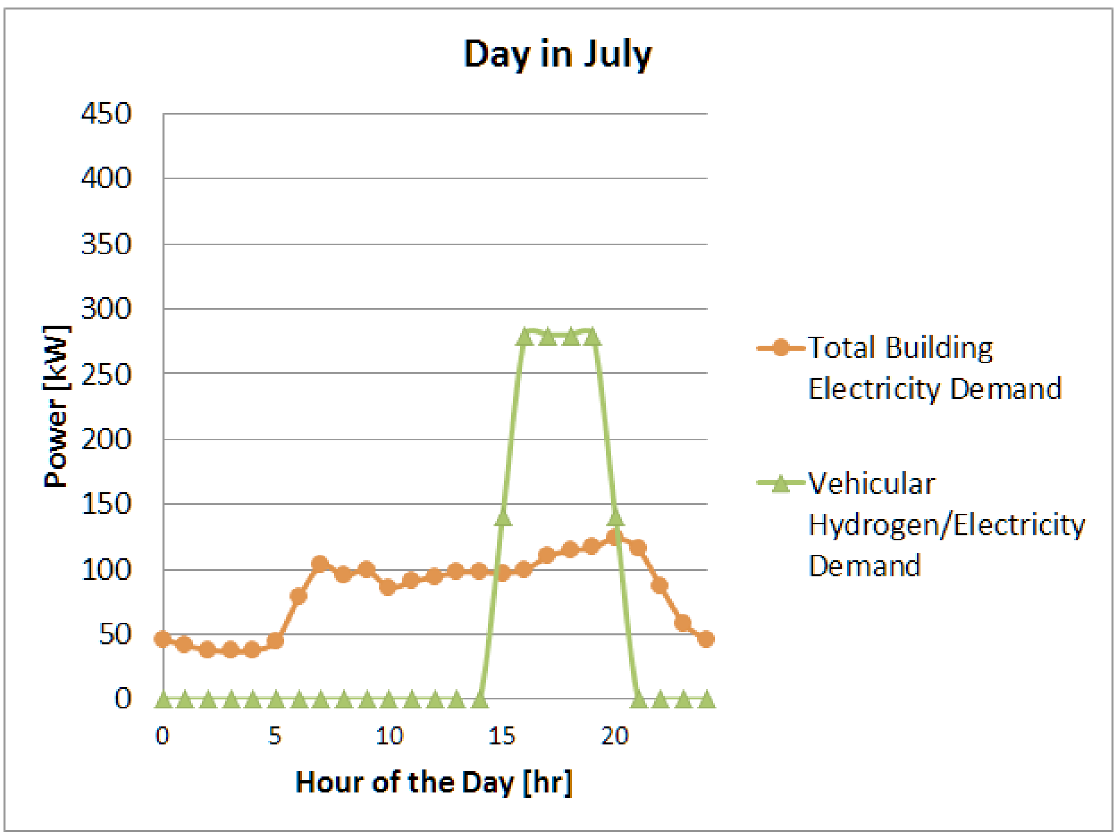


Figure 11. Example vehicular hydrogen/electricity demand profile (4,000 m^2 PV system)

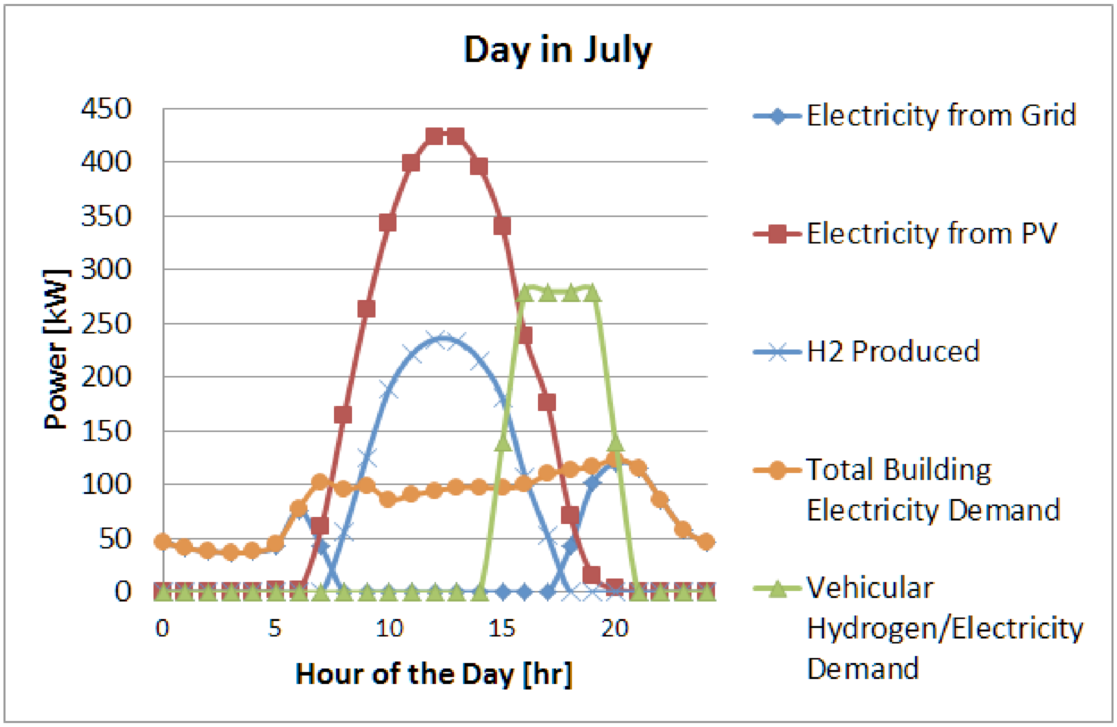


Figure 12. Building electricity demand, vehicular hydrogen/electricity demand, PV and grid electricity supply, and hydrogen produced (or electricity to storage) during a typical day in July ($4{,}000\ m^2$ PV system) – Hydrogen Case 1

Table 7. Summary of Energy Flows for Vehicle-Refueling System (Hydrogen and Battery/Electric Systems)—Case 1

Equipment/System	System Size	Yearly Output	Capacity Factor (% of Max Output during Operation, [h/yr])	Percent of Building Load
1,200 m^2 PV System				
PV system	1,200 m^2 (~ 183 kW peak rated output)	286,704 kWh	18	50 (total) 35 (direct supply)
Electrolyzer (H_2 system)	127 kW input	1,804 kg	36 [1,904]	—
Hydrogen storage (H_2 system)	75 kg	~ 1 cycle per day	—	—
Vehicle electricity (battery system)	—	61,726 kWh	—	—
Battery storage (battery system)	589 kWh	~ 1 cycle per day	—	—
Grid	—	370,486 kWh	—	65
4,000 m^2 PV System				
PV system	4,000 m^2 (~ 611 kW peak rated output)	955,681 kWh	18	167 (total) 47 (direct supply)
Electrolyzer (H_2 system)	560 kW input	14,564 kg	40 [3,265]	—
Hydrogen storage (H_2 system)	85 kg	~ 1 cycle per day	—	—
Vehicle electricity (battery system)	—	500,755 kWh	—	—
Battery storage (battery system)	2,954 kWh	~ 1 cycle per day	—	—
Grid	—	303,744 kWh	—	53
7,000 m^2 PV System				
PV system	7,000 m^2 (~ 1,069 kW peak rated output)	1,672,442 kWh	18	292 (total) 51 (direct supply)
Electrolyzer (H_2 system)	1,013 kW input	29,274 kg	39 [3,669]	—
Hydrogen storage (H_2 system)	165 kg	~ 1 cycle per day	—	—
Vehicle electricity (battery system)	—	1,008,212 kWh	—	—
Battery storage (battery system)	5,530 kWh	~ 1 cycle per day	—	—
Grid	—	283,082 kWh	—	49

Table 8. Summary of Energy Flows for Vehicle-Refueling System (Hydrogen and Battery/Electric Systems)—Case 2

Equipment/System	System Size	Yearly Output	Capacity Factor (% of max output during operation, [hrs/year])	Percent of Building Load
1,200 m^2 PV System				
PV system	1,200 m^2 (~ 183 kW peak rated output)	286,704 kWh	18	50 (total) 21 (direct supply)
Electrolyzer (H_2 system)	105 kW input	3,541 kg	36 [3,137]	—
Hydrogen storage (H_2 system)	90 kg	~ 1 cycle per day	—	—
Vehicle electricity (battery system)	—	121,936 kWh	—	—
Battery storage (battery system)	2,493 kWh	~ 1 cycle per day	—	—
Grid	—	453,078 kWh	—	79
4,000 m^2 PV System				
PV system	4,000 m^2 (~ 611 kW peak rated output)	955,681 kWh	18	167 (total) 27 (direct supply)
Electrolyzer (H_2 system)	554 kW input	16,985 kg	38 [3,907]	—
Hydrogen storage (H_2 system)	95 kg	~ 1 cycle per day	—	—
Vehicle electricity (battery system)	—	585,475 kWh	—	—
Battery storage (battery system)	3,305 kWh	~ 1 cycle per day	—	—
Grid	—	419,957 kWh	—	73
7,000 m^2 PV System				
PV system	7,000 m^2 (~ 1,069 kW peak rated output)	1,672,442 kWh	18	292 (total) 28 (direct supply)
Electrolyzer (H_2 system)	1,013 kW input	31,898 kg	38 [4,110]	—
Hydrogen storage (H_2 system)	165 kg	~ 1 cycle per day	—	—
Vehicle electricity (battery system)	—	1,095,214 kWh	—	—
Battery storage (battery system)	5,914 kWh	~ 1 cycle per day	—	—
Grid	—	410,195 kWh	—	72

2.4 Comparison of Load Leveling and Vehicle-Refueling Systems

The general strategy employed for the load leveling cases was to minimize and smooth the electricity demand that must be met by the grid. In the vehicle refueling cases, the strategy focused on producing vehicle fuel (either hydrogen or electricity) exclusively from the renewable resource in the most cost effective manner. Figure 13 illustrates the effect of each strategy on the amount of grid electricity purchased monthly for the 4,000 m^2 case. Note that some grid electricity is purchased almost every month for the storage scenario case, especially during the winter, even though the solar panels produce almost double the building load overall and produce nearly 50% more electricity than the building load during the winter. This occurs because the storage system, which is large enough to accommodate seasonal variations in PV system output (see Figure 14) for the energy storage scenario, gradually empties in the fall as PV daily electricity production decreases. During the winter, only electricity produced that day is available for electricity generation from the hydrogen fuel cell in the evening and overnight. On a cloudy day when little electricity is generated by the PV panels, there is no “cushion” of hydrogen in storage and electricity must be purchased. For the two hydrogen vehicle cases, the electricity used to generate hydrogen is permanently removed from electrical system for the building and grid. There is no electricity generation from the storage system. The grid electricity needed to satisfy the building load is reduced because some electricity from the PV system can be directly routed to the building. Less grid electricity is required for hydrogen vehicle case 1 (purple line in Figure 13) than for hydrogen vehicle case 2 (green line in Figure 13) because the electricity from the solar panels is routed to the building for a longer period each day in case 1. In all cases, the grid demand is reduced and smoothed as compared to the building demand alone.

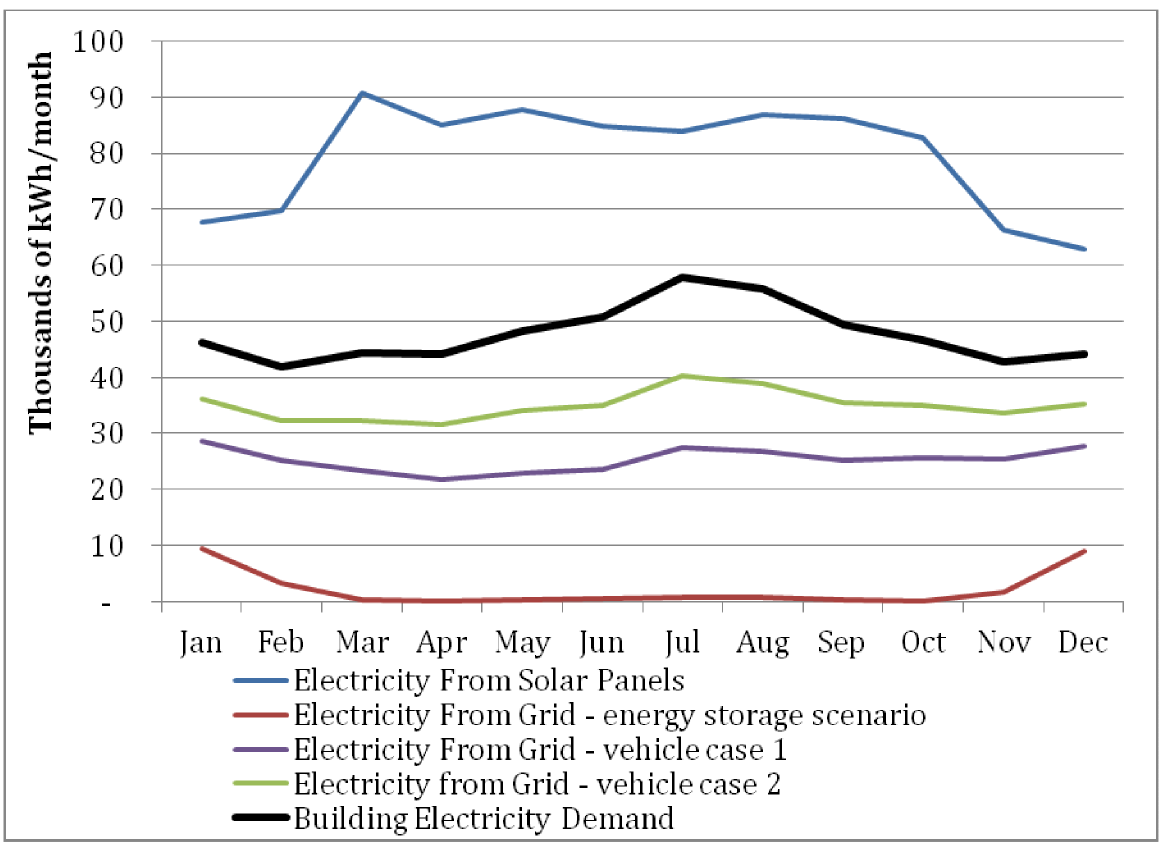


Figure 13. Monthly PV system output and electricity from the grid – 4,000 m^2 PV system

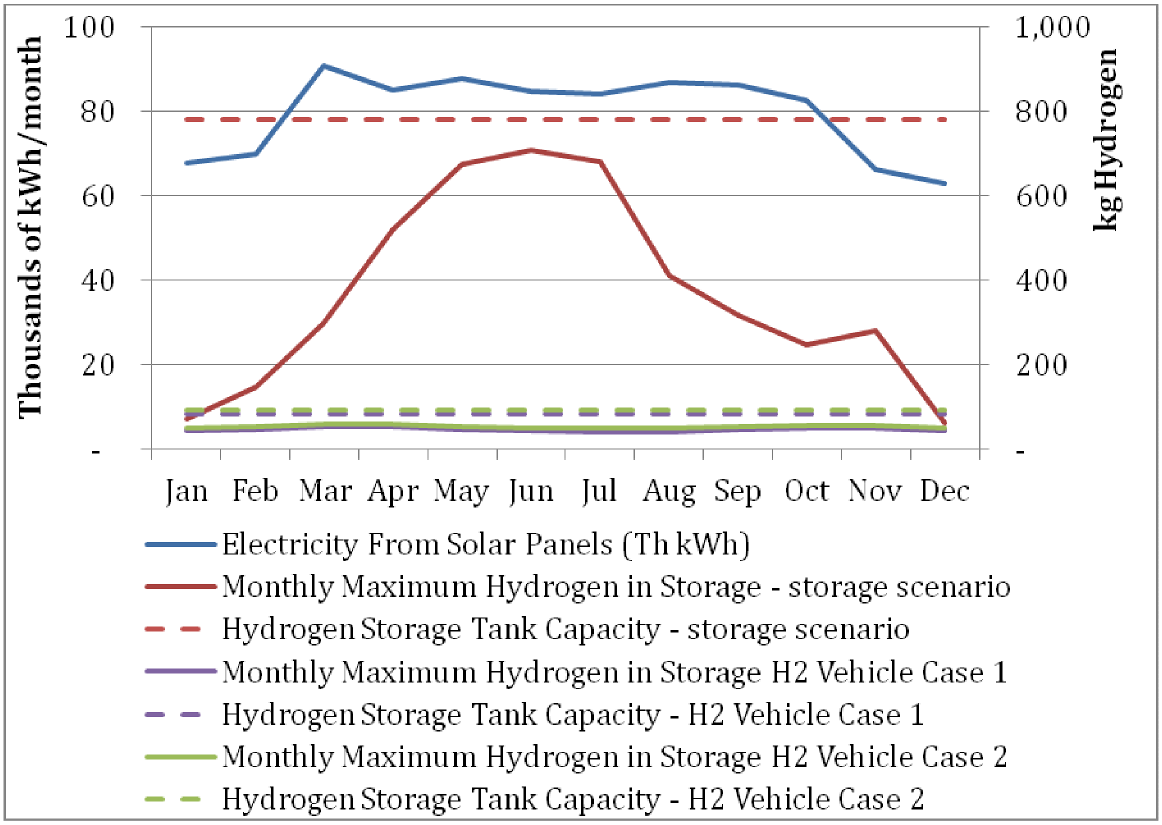


Figure 14. Monthly maximum hydrogen in storage for various scenarios – 4,000 m^2 PV system

The smoothing effect of energy storage and diversion of excess PV production to vehicles is illustrated in Figure 15, which plots the maximum daily fluctuations in PV output and grid interactions for the 4,000 m^2 PV system case. Electricity that would have been routed to the grid in the absence of a storage or vehicle refueling system is shown in orange. With no storage or vehicle refueling system, the maximum delta, within a single day, between drawing electricity from the grid and routing electricity to the grid is 633 kW. With storage, the maximum is 103 kW and with either of the hydrogen vehicle refueling systems, the maximum is 131 kW.

Monthly PV output and electricity from the grid for the 7,000 m^2 case is shown in Figure 16. Monthly maximum hydrogen in storage is shown in Figure 17.

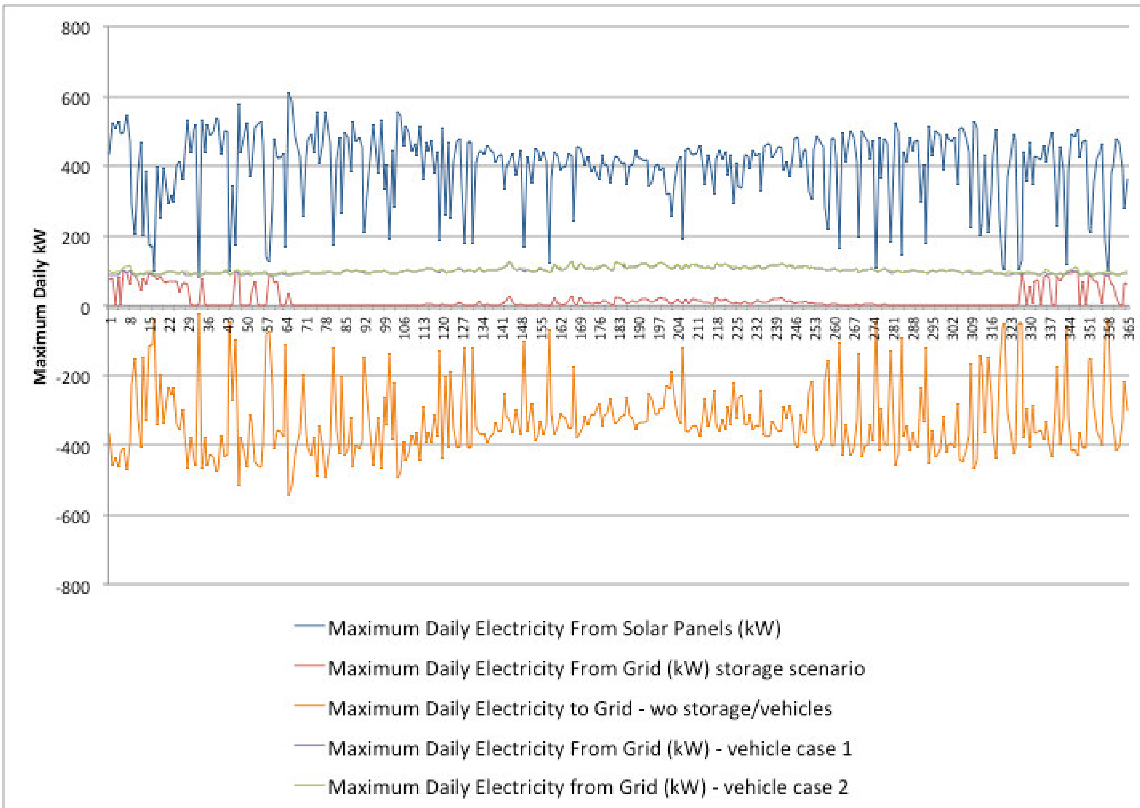


Figure 15. Maximum daily fluctuations in PV system output and grid interactions – 4,000 m^2 PV system

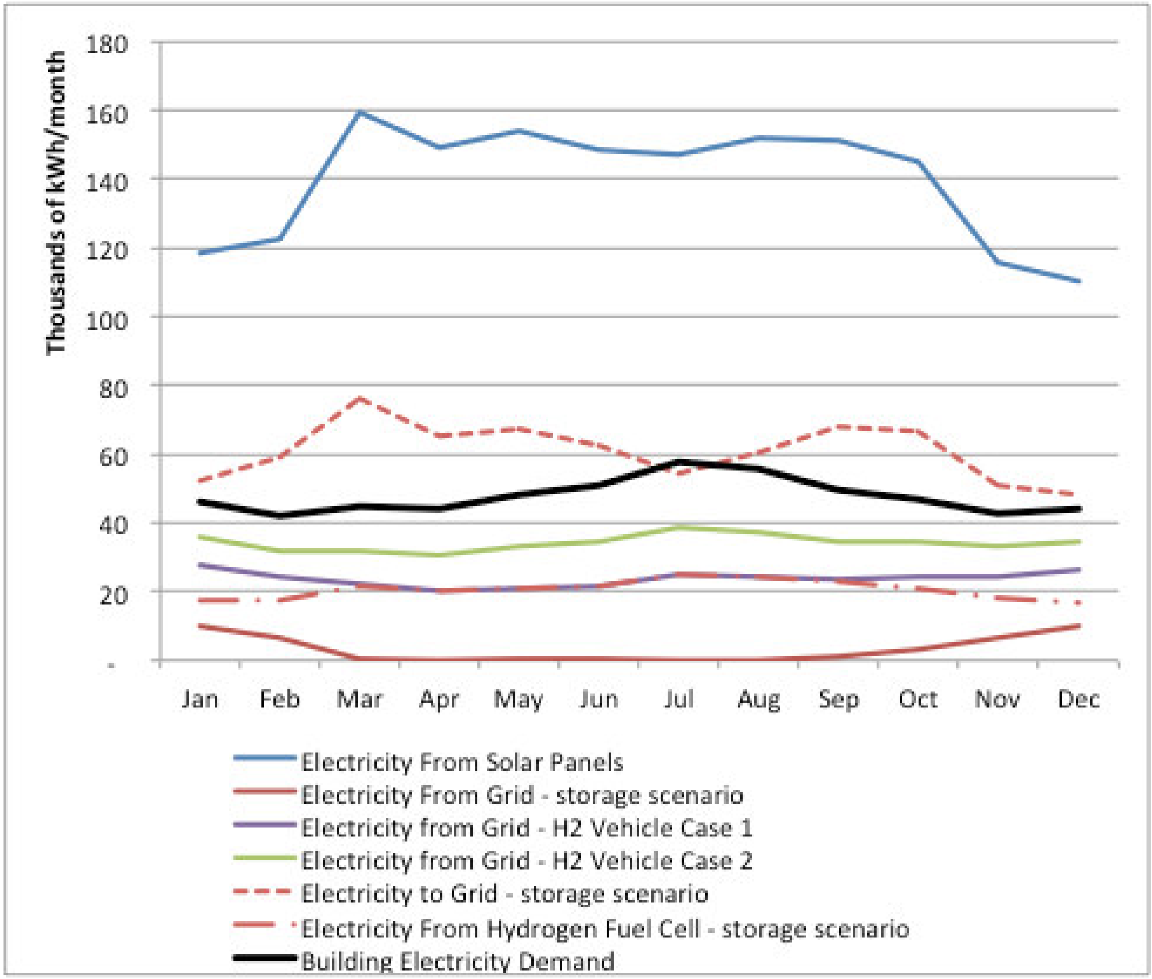


Figure 16. Monthly PV system output and electricity from the grid – 7,000 m^2 PV system

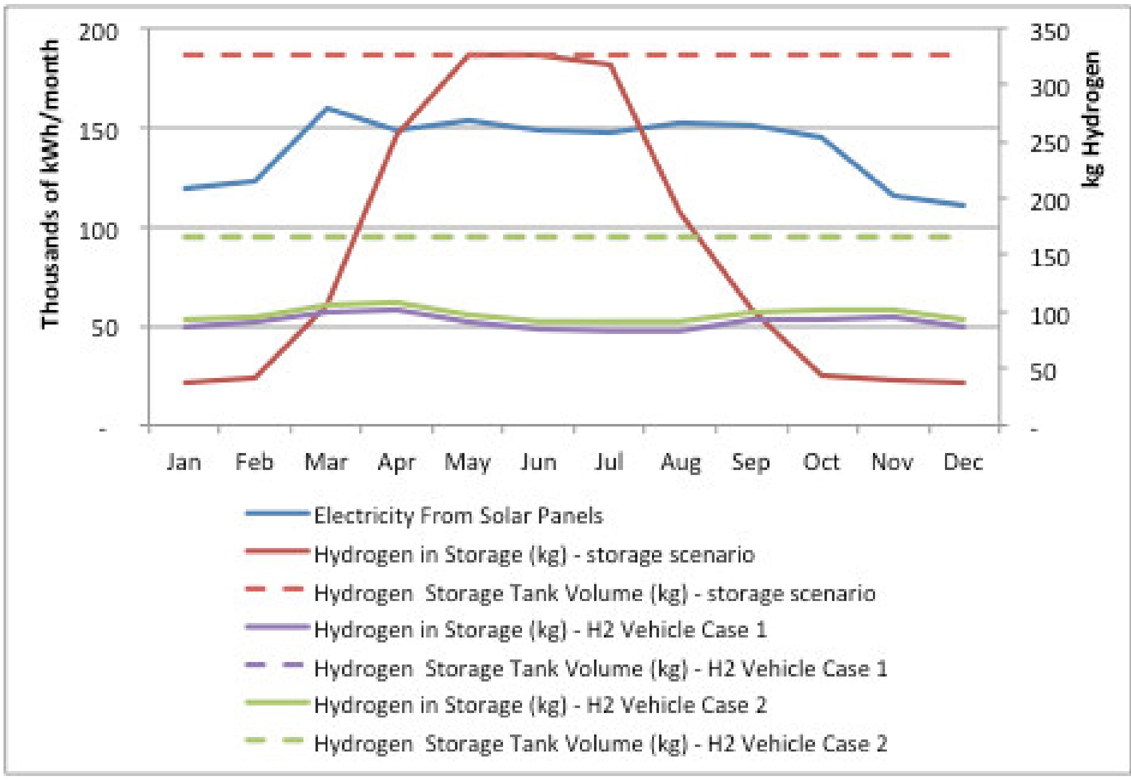


Figure 17. Monthly PV system output and electricity from the grid – 7,000 m^2 PV system

3 Cost Analysis Results

A modified version of the NREL Fuel Cell Power (FCPower) spreadsheet model was used as the basis for the economic analyses for the community energy storage scenarios. The FCPower model incorporates the lifecycle discounted cash flow methodology developed for the H2A (www.hydrogen.energy.gov/h2a_production.html) hydrogen production model. A detailed explanation of the economic methodology is provided in an NREL technical manual for the economic evaluation of energy efficiency and renewable energy projects (Short et al. 1995). Cash flows including revenues, variable and fixed operating expenses (fuel, labor, interest on debt, taxes, etc.), capital expenditures and repayment of principal are aggregated yearly over the lifetime of the project. This methodology captures the time dependence of costs and revenues over the life of the project. For example, the methodology accurately captures costs associated with replacement of equipment components at specific times in the future. All per kWh or per kg costs presented are levelized costs including all direct and indirect costs and operating expenses over the life of the system.

An initial analysis of the PV system alone (without a storage system) was performed to establish a baseline cost for the PV-generated electricity. Because the PV system capital costs are assumed to be the same on a $/Watt basis for all three system sizes, the LCOE of electricity generated over the 30 year assumed life of the system, is the same - 15 ¢/kWh for all of the systems. This value was used as the "selling price" for electricity routed directly to the building. In this way, the cost of the solar system was apportioned between the building and the storage/vehicle fuel production system. The apportioned cost of the solar system is included in the LCOE results of the storage or fuel production cases unless specifically stated otherwise.

Table 9 lists the equipment and associated costs for the community energy storage scenarios. All equipment costs are assumed to scale linearly within the size ranges of the analysis except control and safety equipment and electrical upgrades for the hydrogen systems, which are assumed to be fixed costs. Table 10 lists the financial parameters used in the analysis.

Table 9. Equipment Costs for Load-Leveling and Vehicle-Refueling Scenarios

Equipment Costs $2010					
	Unit	**Equipment Size Range**	**Cost Unit**	**Cost (Installed)** [replacement/ refurbishment % of installed cost/interval]	**Installed Cost Reference**
Electrolyzer	kW	105 – 1,013	$/kW input	~$600 [25%/10 years]	HTAC (2011) ($750 including all BOP and indirect costs. DOE Independent Review (2009) installed cost ~$540/kW ($2010))
Hydrogen storage tanks (load leveling)	kg	16 – 780	$/kg H_2	~$1,350	H2A (2012). Installed cost for low pressure storage
Hydrogen storage tanks (vehicle refueling)	kg	75 – 165	$/kg H_2	~$1,350 – 1,400	H2A (2012). Installed cost for low pressure and cascade storage
Hydrogen storage compressor + balance of plant, installed (load leveling)	kW	4 – 20	$/kW	$11,000 – 7,200 [100%/10 years]	H2A (2012)
Hydrogen storage compressor (vehicle refueling)	kW	5 – 44	$/kW	$10,400 -$2,600	H2A (2012)
Hydrogen fuel cell	kW	15 – 125	$/kW	~$950 [30%/15 years]	HTAC (2011)
Hydrogen dispenser	—	1	$/unit	~$64,000	H2A (2012)
Zinc-air battery	kWh	600 – 6,000	$kWh	$315	Rastler (2010). Based on max kWh in "storage" at any time
Electrical upgrades and charging stations	—	—	$	5% of installed battery cost	HTAC (2011)
PV system	kW	180 – 1,070	$/kW installed	~$2,500	HTAC (2011) (Barbose et al. [2012] installed cost for >100kW residential or commercial systems ~$4.75/W $2011)
Indirect Costs	Site preparation, engineering, contingency, permitting		% of installed capital cost	28%	H2A (2012)
Energy Cost					
Levelized cost of grid electricity for building supply without a PV/storage system	$0.12			$/kWh	

Revenue for electricity sold	$0.12	$/kWh

Notes and assumptions:

1. Vehicle-refueling storage systems include low-pressure tanks (~$1,000/kg) and one cascade storage system (~$1,700/kg, 65 kg H_2 in a three-tank system).
2. For the vehicle-refueling systems, one primary compressor is assumed for both low-pressure and cascade storage: ~2.4 kW compressor power/(kg/h) H_2 flowrate.
3. The compressor system assumes a 200 psi input pressure and a 3,600 psi output pressure.
4. Model parameters are based on a 2020 planning timeframe.
5. Model parameters assume a manufacturing scale of 1,000 systems per year.

Table 10. Financial Analysis Parameters

Model Parameter	Units	Value
Insurance	% of initial direct capital	2%
Annual O&M rate	% of initial direct capital	2%
Inflation rate	%	2%
Total tax rate		0%
Reference dollar year for costs		2010
Financing	Debt financing, 15 year	100%
Interest rate on debt		8%
Real, after-tax rate of return required		0%
System Life	years	30

Notes and assumptions:

1. Annual O&M costs are calculated as a % of initial capital, and include the periodic replacement of components. Compressor system cost is scaled on the hydrogen flow rate in kg/day of flow.

3.1 Load Leveling

The levelized cost of electricity from the storage system for each of the scenarios is listed in Table 11. The total direct capital cost and LCOE for the system including the PV system cost are calculations of the total cost of energy supplied by the combination of the PV system directly supplying electricity to the building plus the cost of routing some of the electricity through the storage system. Credit is taken for any electricity that is sold back to the grid. Electricity sold back to the grid is assumed to be sold at 12 ¢/kWh, which is the same price as supplementary electricity purchased from the grid. For the total direct capital cost and LCOE without the PV system costs, the costs presented are for the storage system only and the LCOE applies only to the electricity output from the storage system. In this case, electricity from the PV system to the electrolyzer is assumed to be "free" and the costs presented represent only the cost of purchasing the equipment and non-energy operating costs for the storage system. If the electricity that is routed to the storage system could be sold for 6 ¢/kWh instead, the cost of electricity to the electrolyzer could be assumed to be worth 6 ¢/kWh. Recalculating the costs assuming that electricity routed to the electrolyzer costs 6 ¢/kWh, and using the 1,200 m^2 PV system case as an example, illustrates the effect of the additional cost. For the 1,200 m^2 PV case, about 32,000 kWh of electricity are produced from the storage system. At zero cost for the electricity supply to the electrolyzer, the cost of output electricity is about $1.09 per kWh. This cost increases to

$1.26/kWh if the input electricity is 6 ¢/kWh. The output electricity cost is highly sensitive to the cost of input electricity because of the inefficiency of the electrolyzer/storage/hydrogen fuel cell system. In this case, the round trip efficiency of the storage system is between 35% and 40%, resulting in about 2.5 kWh electricity used for every kWh of electricity produced from the fuel cell.

The LCOE for the full systems increases for the larger systems because the high PV system costs, but variations in equipment utilization make the 7,000 m^2 system overall slightly lower cost than the 4,000 m^2 system. The 7,000 m^2 system has better utilization of the electrolyzer than the 4,000 m^2 system; 3,619 hours/year operating at an average of 84% of peak output for the 7,000 m^2 system and 3,265 hours/year operating at an average of 39% of peak output for the 4,000 m^2 system. However, the fuel cell utilization is better for the 4,000 m^2 system than for the 7,000 m^2 system (5065 hours/year at 55% of peak [4,000 m^2 system], 4,388 hours/year at 45% of peak [7,000 m^2 system]). In the case of the 7,000 m^2 system, electricity produced by the PV system must be sold to the grid at a lower cost than the cost of generating it (12 ¢/kWh v 15 ¢/kWh respectively).

In contrast, focusing only on the cost of storing electricity shows the opposite trend. The storage system is used much more effectively for higher penetrations of PV so the costs of stored electricity decrease. Careful attention must be paid to matching the storage system to the particular application. There are many variables including the electrolyzer size, storage system size, and fuel cell size that must be considered together with the building load characteristics and PV system output to optimize the system to achieve the goals for the application.

Table 11. Load-Leveling System Costs With and Without PV Costs Included

Scenario	Total Direct Capital Cost Including PV System ($000)	LCOE of Electricity (Direct Supply + Electricity from Storage) (¢/kWh)	Total Direct Capital Cost without PV System ($000)	LCOE of Stored Electricity (¢/kWh)*
1,200 m^2 PV/storage system	$727	33	$271	109
4,000 m^2 PV/storage system	$2,958	57	$1,438	62
7,000 m^2 PV/storage system	$3,393	45	$733	36

* Levelized costs include all direct and indirect costs for the apportioned cost of the PV system, hydrogen/battery production, storage and delivery, and replacement and operating expenses over the life of the system.

The equipment cost breakdown for scenarios analyzed is shown in Figure 18. The balance of plant components including electrical upgrades and control and safety equipment are included in the category labeled "Hydrogen Compressor." In these scenarios, the hydrogen storage system (compressor and storage tanks) comprises more than 50% of the non-PV system costs. The electrolyzer cost is higher than the fuel cell cost in all cases even though the electrolyzer is lower cost than the hydrogen fuel cell on a per kW basis. This occurs because the electrolyzer must be sized to capture electricity produced by the PV system during a relatively short period in the mid-day when PV output peaks and demand is relatively low. In contrast, the hydrogen fuel cell can be sized to slowly feed electricity back to the building load during a relatively long period when demand is steady and there is no PV output. The results of an analysis of the sensitivity of the 4,000 m^2 PV system case output electricity cost to equipment cost is presented in Figure 19.

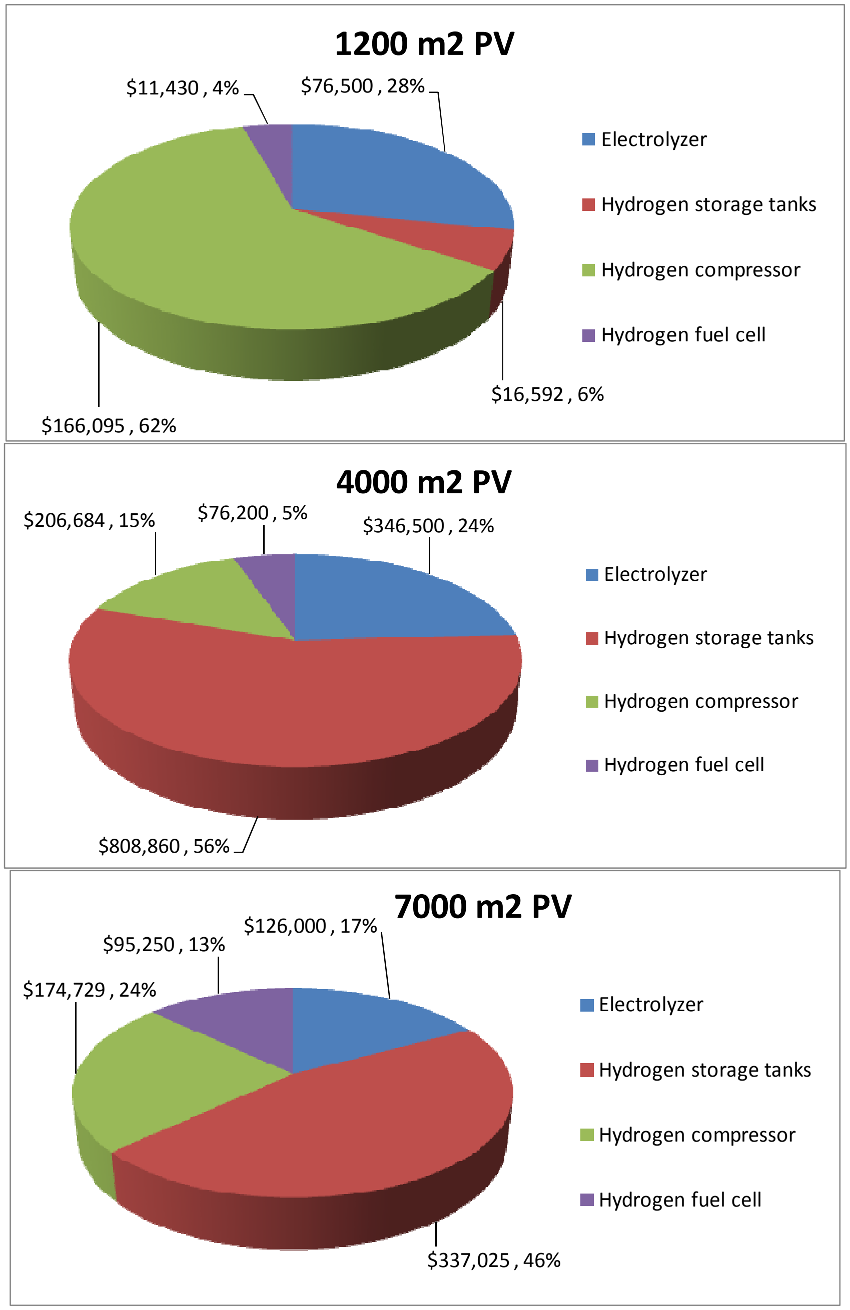


Figure 18. Capital cost breakdown for hydrogen storage systems for 1,200 m^2 PV system (top), 4,000 m^2 PV system (center), and 7,000 m^2 PV system (bottom)

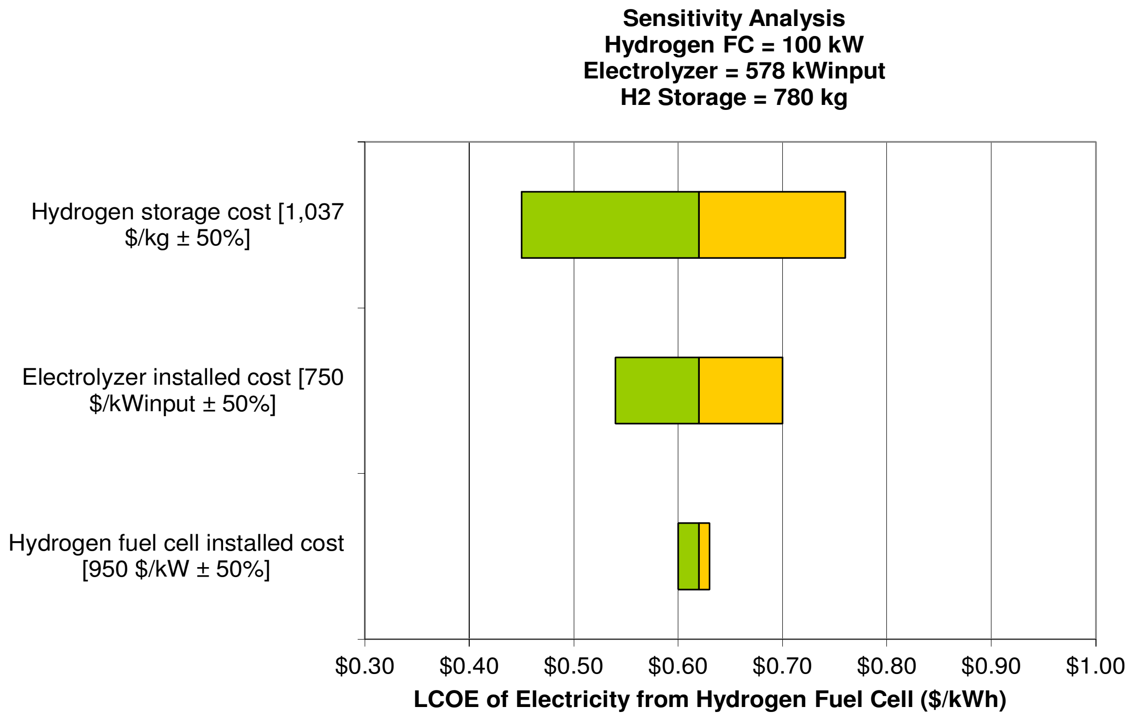


Figure 19. Sensitivity of output electricity LCOE to equipment cost for the 4,000 m^2 PV system case

3.2 Vehicle Refueling

Figure 20 shows the total system capital costs for Case 1. The PV system dominates the capital costs followed, for the larger systems, by the electrolyzer. Figure 21 shows the capital cost breakdown for the hydrogen system only. The electrolyzer accounts for 16% (1,200 m^2 PV system), 40% (4,000 m^2 system), and 45% (7,000 m^2 system) of the hydrogen system costs. For the smallest PV system, hydrogen storage accounts for the largest capital cost (22%).

Figure 22 compares the hydrogen system capital costs of Case 1 versus Case 2. For the smallest PV system, Case 2 capital costs are substantially higher, primarily owing to higher hydrogen storage and electrolysis costs. For this system, 96% more hydrogen is produced annually in Case 2 than in Case 1 because the extra PV output used to produce hydrogen before noon in Case 2 accounts for almost as much total hydrogen production as the PV output in excess of the building load. Thus, the electrolyzer and hydrogen storage must be substantially larger in Case 2 than in Case 1 to accommodate the higher hydrogen production rates and extra hydrogen storage. As the PV system size increases, the contribution of the extra morning hydrogen production becomes smaller. For the 4,000 m^2 system, Case 2 produces only 17% more hydrogen annually than Case 1, and Case 2 capital costs are only slightly higher. For the 7,000 m^2 system, Case 2 produces only 9% more than Case 1, and the capital costs are almost identical.

Table 12 summarizes the Case 1 and Case 2 cost results for both the hydrogen and battery-electric vehicle refueling systems. On a per-mile basis, electric storage/refueling is 30 to 60 percent of the cost of hydrogen storage/refueling. The largest differential is for the 1,200 m^2 PV system, for which the hydrogen capital cost is about twice as high as the battery-electric capital cost (Figure 23). For the 4,000 and 7,000 m^2 PV systems, the hydrogen capital costs are lower than the battery-electric capital costs; however, the higher efficiency of the battery-electric vehicle system (29 kWh/100 miles for EVs versus 55.6 kWh/100 miles for FCEVs[6]) still results in a lower per-mile cost for the battery-electric vehicle system.

In both cases for the hydrogen and electric systems, diverting more electricity from the PV system for vehicle refueling improves the economics; this effect is more pronounced for the hydrogen system. The best hydrogen cost is from the Case 2 7,000 m^2 PV system. In this scenario, about 90% of the PV output goes to hydrogen production or battery storage, and the PV system supplies 28% of the building load. The hydrogen system produces about 32,000 kg of hydrogen per year (about 90 kg/day), enough to supply 159 vehicles, at a cost of $11/kg or 19 ¢/mile.

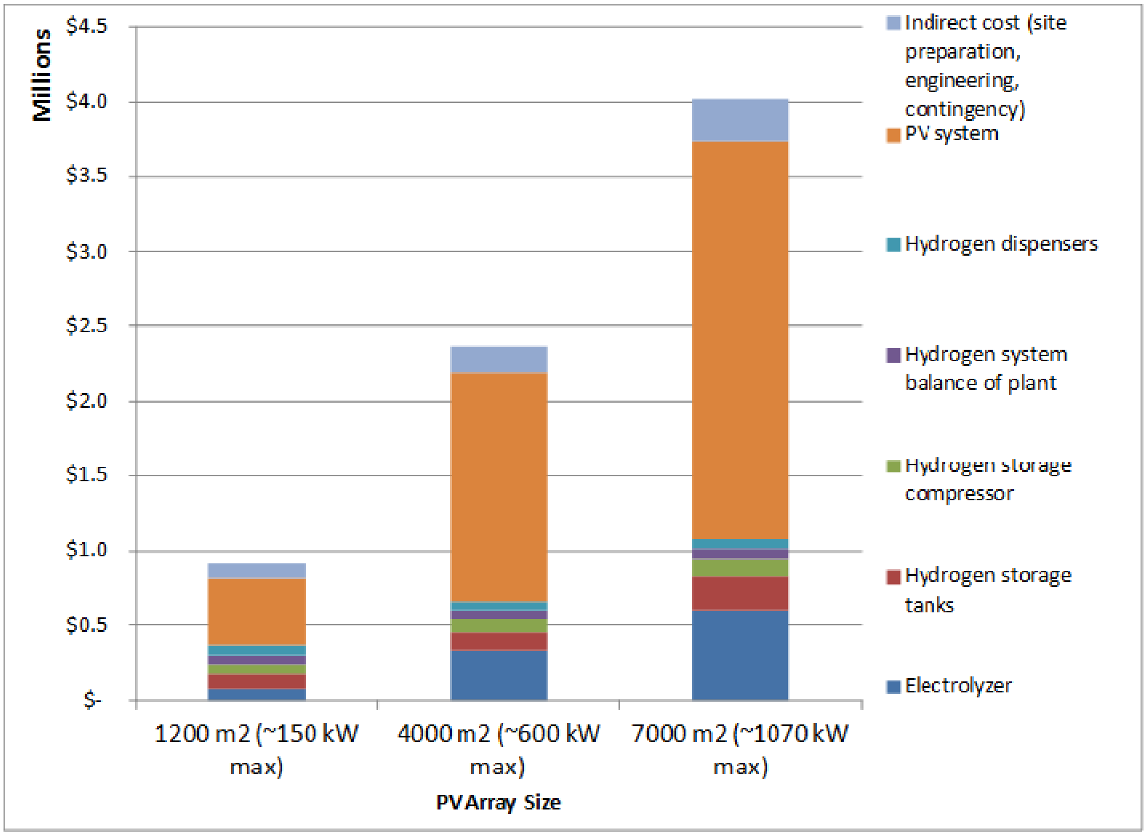


Figure 20. Total PV-hydrogen system capital costs (Case 1)

[6] FuelEconomy.gov accessed 6/20/2013.

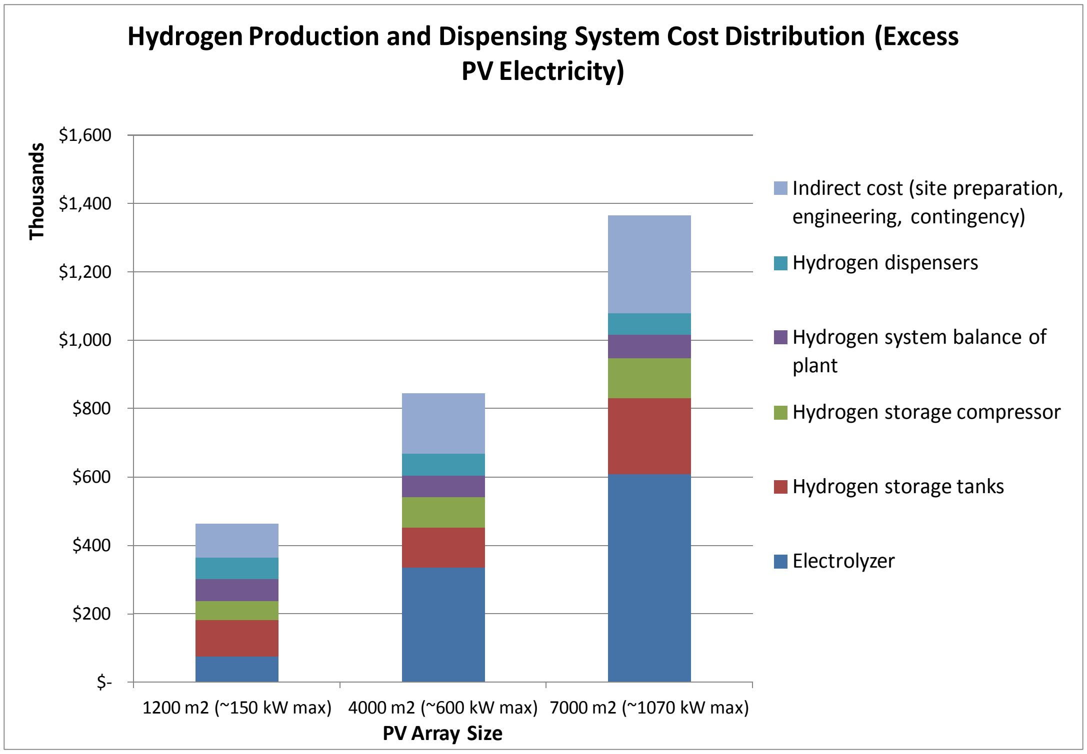


Figure 21. Hydrogen system capital costs (Case 1)

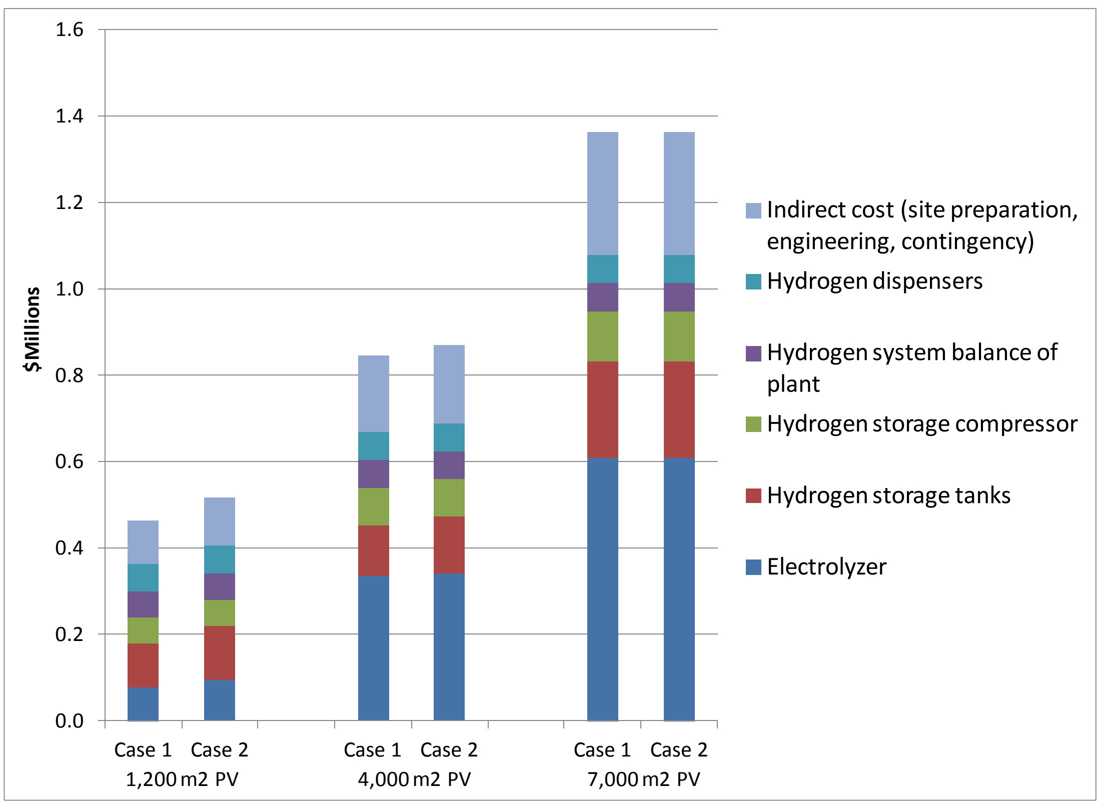


Figure 22. Comparison of hydrogen system capital costs between Case 1 and Case 2

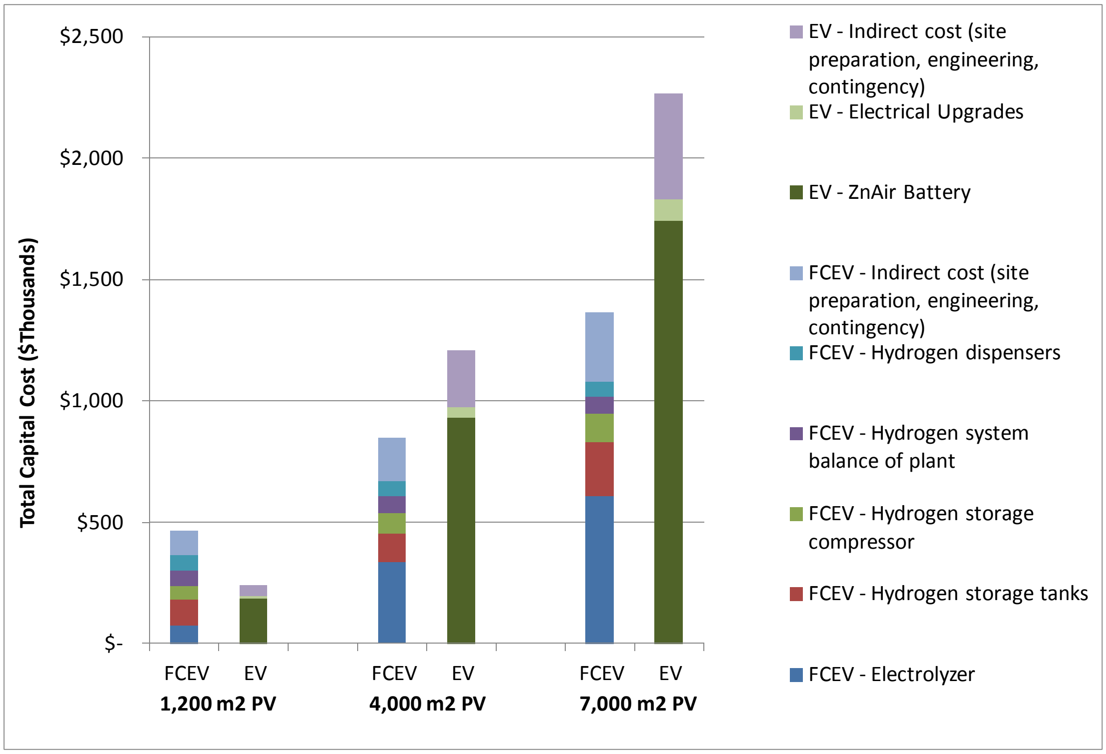


Figure 23. Capital costs of hydrogen (FCEV) and battery-electric (EV) systems, Case 1

Table 12. Summary of Vehicle Refueling Cost Results

Hydrogen for Fuel Cell Vehicles*								
	Case 1 (Excess Electricity)				Case 2 (Excess Electricity + Morning Output)			
PV Size (m^2)	Production (kg H_2/yr)	Vehicles Served	H_2 LCOE ($/kg)	H_2 Cost (¢/mi)	Production (kg H_2/yr)	Vehicles Served	H_2 LCOE ($/kg)	H_2 Cost (¢/mi)
1,200	1,804	9	34	56	3,541	17	22	38
4,000	14,564	72	13	22	16,985	84	12	21
7,000	29,274	146	12	20	31,898	159	11	19
Electricity for Battery-Electric Vehicles*								
	Case 1 (Excess Electricity)				Case 2 (Excess Electricity + Morning Output)			
PV Size (m^2)	Production (kWh/yr)	Vehicles Served	Elec. LCOE ($/kWh)	Elec. Cost (¢/mi)	Production (kWh/yr)	Vehicles Served	Elec. LCOE ($/kWh)	Elec. Cost (¢/mi)
1,200	61,726	17	0.57	17	121,936	35	0.45	13
4,000	500,755	143	0.41	12	585,475	168	0.40	12
7,000	1,008,212	289	0.39	11	1,100,877	316	0.39	11

* Levelized costs include all direct and indirect costs for the apportioned cost of the PV system, hydrogen/battery production, storage and delivery, and replacement and operating expenses over the life of the system. For the 4,000

and 7,000 m^2 PV systems, the hydrogen capital costs are lower than the battery-electric capital costs; however, the higher efficiency of the battery-electric vehicle system (29 kWh/100 miles for EVs versus 55.6 kWh/100 miles for FCEVs[7]) still results in a lower per-mile cost for the battery-electric vehicle system.

4 Conclusions and Future Work

These simple analyses show the potential application of hydrogen production, storage, and electricity-generation technologies for community load leveling and vehicle refueling. Although the results do not show a clear advantage for hydrogen load leveling or vehicle refueling, the analysis does indicate that the economics could be improved especially for larger systems.

The primary goal of the load-leveling scenario was to evaluate storage systems for load leveling under the constraint of a limited grid/transformer size. The systems were sized to meet this goal, but not fully optimized for cost. The results of the analyses indicate that storage systems are more cost effective for higher penetrations of renewable electricity generation. In all cases, however, the electricity produced by the storage system was more expensive than grid electricity. Therefore, the storage system must provide benefits in addition to cost, such as relieving grid congestion and/or providing backup power in order to be cost effective. A sensitivity analysis for equipment costs for the 4,000 m^2 energy storage case revealed that LCOE of output electricity was most sensitive to the hydrogen storage tank cost (Figure 19). However, the overall system cost is also highly dependent on the configuration of the system and the relative sizes/capacities of the various pieces of equipment as shown by the wide variation in the relative sizes of equipment for the three PV system sizes analyzed (Figure 18).

In all scenarios, the storage system reduced peaks and valleys in grid demand and energy fed onto the grid (see Figure 15). The leveling effect was the most pronounced for the larger systems. However, the analysis also showed that additional optimization and/or control of the storage systems would be needed to completely eliminate large spikes in energy flow. For the 4,000 m^2 PV system case, which is most closely matched to the building demand, the storage system and vehicle systems reduced the daily fluctuations in grid demand by almost 80% and completely eliminated reverse flow of electricity to the grid. The 4,000 m^2 system storage scenario was also able to accommodate the seasonal variation in PV output, allowing for all of the energy produced by the PV system throughout the year to be used onsite. Storage that can smooth seasonal variations as well as daily variations in PV system output may be advantageous for very high levels of PV penetration.

This brief analysis shows that community level hydrogen refueling using only renewably generated electricity could be accomplished. For the 4,000 m^2 PV system case, the number of fuel cell vehicles that could be refueled roughly matches the total number of vehicles expected for the community size modeled (100 households). The vehicle refueling scenarios were configured so that the storage systems, either hydrogen or battery) were cycled approximately daily with a fairly generous “cushion” for expected fluctuations in demand over the course of a few days or a week. The analysis does not assume that the additional storage accounts for seasonal variations in hydrogen/electricity demand or production. Month to month variations in production are not large. However, the high and low production months (March and December respectively) only roughly correspond to expected high and low demand months (June–August

[7] FuelEconomy.gov accessed 6/20/2013.

and November–January respectively). There is also a predictable dip in PV output during the hottest part of the summer, when fuel demand is expected to peak. Although the analysis did not explicitly address seasonal variations in production or demand, it is likely that the additional storage modeled would be sufficient to accommodate them. The vehicle refueling scenarios also provide as much smoothing of the PV system output/grid demand as the energy storage scenarios (see Figure 15). This smoothing of PV/grid interactions could be vital for integration of high levels of distributed PV.

The vehicle-refueling analysis shows the potential for community-level hydrogen refueling using only renewably generated electricity (Table 12). With the 4,000 m^2 PV system, the number of fuel cell vehicles served (70 – 80) roughly matches the modeled community size (100 households). The levelized hydrogen cost ranges from $34/kg ($1.01/kWh) for the 1,200 m^2 Case 1 system to $11/kg ($0.34/kWh) for the 7,000 m^2 Case 2 system. The cost of battery storage of electricity for electric vehicles ranges from $0.57/kWh to $0.39/kWh, also decreasing with increasing system size. The hydrogen system cost reduction for the larger systems is due, as for the load leveling system, to better utilization of the equipment. The hydrogen system configuration is also more flexible than the battery system because there are more independent pieces of equipment. For small systems, this is a disadvantage, but for larger systems the increased flexibility reduces costs because an incremental increase in hydrogen storage capacity per kWh (hydrogen tank) is less expensive than an incremental (per kWh) increase in electrochemical storage. Even though the hydrogen system is lower cost than the battery system for the largest storage case, the electric vehicle is less expensive on a fuel ¢/mile basis because of its higher efficiency in comparison to the fuel cell vehicle.

4.1 Future work

This analysis did not show a clear advantage for hydrogen load leveling or vehicle refueling. However, the analysis does indicate that the economics could be improved, especially for larger systems, with careful optimization of the system configuration and equipment. The following list outlines several areas of further research that might enhance understanding of the economics of community level hydrogen energy:

- Explore more realistic scenarios for dealing with seasonal variation in PV output
- Explore methodologies for optimizing hydrogen system configuration
- Explore the impact of incentives and net metering for economics.

5 References

Barbose, G.; Darghouth, N.; Wiser, R. (November 2012). Tracking the Sun V: An Historical Summary of the Installed Cost of Photovoltaics in the United States from 1998 to 2011. Berkeley, CA: Lawrence Berkeley National Laboratory.

DOE Independent Review. (September 2009). *Current (2009) State-of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis*. NREL/BK-6A1-46676. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy10osti/46676.pdf.

FCPower Model. (2012). Molten Carbonate Fuel Cell, version 1.2 (Excel file). http://www.hydrogen.energy.gov/fc_power_analysis.html.

Field, K.; Deru, M.; Studer, D. (2010). *Using DOE Commercial Reference Buildings for Simulation Studies*. Preprint. SimBuild 2010. Golden, CO: National Renewable Energy Laboratory.

H2A Production Model. (2012). Current Forecourt Grid Electrolysis 1500 kg per day version 3.0 (Excel file). http://www.hydrogen.energy.gov/h2a_prod_studies.html.

HTAC. (September 2011). HTAC Energy Storage Working Group discussions.

James, B. D; Perez, J.; Baum, K.N.; Spisak, A.; Sanders, M. (May 2011). *Low Temperature PEM Stationary Fuel Cell System Cost Analysis: Preliminary Results*. DTI Subcontract Report; page 35.

NREL. (2009). Fuel Cell Power Model Case Study Data. http://www.hydrogen.energy.gov/cf/fc_power_analysis_model_data.cfm.

Rastler, D. (December 2010). Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits. EPRI Technical Update.

Short, W.; Packey, D.J.; Holt, T. (1995). *A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies*. Golden, CO, National Renewable Energy Laboratory.

Steward, D.; Saur, G.; Penev, M.; Ramsden, T. (November 2009). *Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage*. NREL/TP-560-46719. Golden, CO: National Renewable Energy Laboratory. http://www.nrel.gov/docs/fy10osti/46719.pdf.

Denholm, P., M. Kuss, et al. Co-benefits of large scale plug-in hybrid electric vehicle and solar PV deployment.

Srivastava, A. K., B. Annabathina, et al. (2010). "The Challenges and Policy Options for Integrating Plug-in Hybrid Electric Vehicle into the Electric Grid." The Electricity Journal **23**(3): 83-91.

Plug-in hybrid electric vehicle may be prime candidates for the next generation of vehicles, but they offer several technological and economical challenges. This article assesses current progress in PHEV technology, market trends, research needs, challenges ahead and policy options for integrating PHEVs into the electric grid.

Department of Energy
Washington, DC 20585

Mr. John Hofmeister
Chairman, Hydrogen and Fuel Cell
Technical Advisory Committee
1302 Waugh Dr., #940
Houston, Texas 77019

Dear Mr. Hofmeister:

Thank you for your December 2013 letter to Secretary Moniz and accompanying summary report from the Hydrogen Enabling Renewables Working Group. The Working Group's expertise and recommendations are valued by the Department and have provided useful insight on the role that hydrogen might play in enabling penetration of renewable energy in the United States.

Increasing penetration of renewable technologies is a key feature in both the recommendations of the Working Group, and in national policies. To address the Working Group's first recommendation: renewables feature strongly in President Obama's Climate Action Plan (CAP). During the President's first term, the United States more than doubled its electricity generation from wind, solar and geothermal technologies, and the President has set a goal to double this number again by 2020. CAP's first of three pillars, "Cutting Carbon Pollution in America," presents "Promoting American Leadership in Renewable Energy" as a key solution pathway. This plan is bolstered by policies to increase permitting for renewable power plants, encourage renewable deployment in the military and federally subsidized housing stock, and improve the permitting process for transmission projects. These policies indicate a long-term plan for increased penetration of renewables in the United States.

The Hydrogen and Fuel Cell Technical Advisory Committee's emphasis on hydrogen energy storage for grid management has provided valuable feedback to the Department's assessment of this technology. In 2014, the Department's Fuel Cell Technologies Office plans to hold a workshop on Hydrogen Energy Storage for Variable Electricity Generation. The recommendations in the Working Group's report, as well as in previous HTAC deliverables, will be reviewed as part of a discussion panel to establish the current status of the technology and lessons learned from past efforts.

The Department agrees that energy storage plays an important role in enabling renewables, and has taken steps to investigate the potential of hydrogen energy storage to manage the impacts of intermittent renewable energy on the grid. The Hawaii Natural Energy Institute (HNEI) has received over $1.8 million from the Department to evaluate hydrogen energy systems as a grid management tool. Among its objectives, this project will compare electrolyzer and battery energy storage systems in their ability to address frequency regulation. The Working Group's recommendations may provide ways to expand on the work done so far to establish the conditions at which hydrogen competes with other energy storage systems. For example, the HNEI project may provide the basis for an economic study to evaluate the integrative benefits of hydrogen storage, as recommended by the Working Group. In addition, the Department has invested $135 million to establish a state-of-the-art Energy Systems Integration Facility at NREL to focus on research, development, and demonstration of integrated energy systems. The facility has unique capabilities to overcome challenges related to integration of renewable energy technologies into the electricity grid and to advance energy storage technologies, including hydrogen.

The Committee's recommendations play a critical role in guiding the Department's activities in support of hydrogen and fuel cell technologies. Please convey my appreciation to the Hydrogen Enabling Renewables Working Group for their valuable recommendations to the Department.

Sincerely,

Reuben Sarkar

Reuben Sarkar
Deputy Assistant Secretary for Transportation
Energy Efficiency and Renewable Energy

Hydrogen and Fuel Cell Technology Advisory Committee

U.S. Department of Energy

November 29, 2013

Honorable Ernest Moniz

Secretary

U.S. Department of Energy

1000 Independence Avenue, SW

Washington, D.C. 20585

Dear Mr. Secretary

The Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) was established by Congress in 2005 to provide you with technical and programmatic advice on hydrogen and fuel cells. HTAC has studied the question of hydrogen energy infrastructure for the past three years. We believe the emerging worldwide effort to deploy a fueling infrastructure to support commercial fuel cell electric vehicle (FCEV) sales represents a leadership opportunity for your Department and for the Obama Administration.

We also believe this is a critical moment. Your words and deeds over the next three years can accelerate the deployment of full-function, no-compromise, zero emission passenger cars, with all the energy and environmental security benefits they bring. Together with battery vehicles, FCEVs can achieve the transition to electric drive that is necessary to accomplish our long term energy policy goals. Conversely, delay or doubt could retard commercialization and perhaps cede the technology leadership to other nations.

The development of FCEVs is a success story for the Department of Energy. It is useful to recall that serious interest in fuel cell power for passenger cars dates back to the DOE's leadership on advanced vehicle technologies, expressed via the Partnership for a New Generation of Vehicles and the Freedom Car and Fuel Partnership. Indeed, the anticipated date for the first commercial sales of FCEVs, adopted by governments around the world and announced by several manufacturers – 2015 – is exactly the target date established by DOE in its 2003 *Fuel Cell Report to Congress.* This vision and leadership, expressed in both Republican and Democratic Administrations, ought to be a source of pride for you and your department, and the foundation for your next steps.

We have developed six specific recommendations for your consideration. Broadly, we believe it is time for the Department to publicly and forcefully restate its commitment to FCEVs, strengthen your collaboration with other nations, and, most importantly, include funding for infrastructure deployment in your 2015 budget and beyond, just as other governments worldwide are doing. This investment ought to be in addition to a revived hydrogen and fuel cell research and development budget. The U.S. budget has declined more than 50% since FY 2009 while research investment is increasing in Europe and Asia, in some countries dramatically. These steps can and should be fully consistent with the regulatory and research programs that underpin the "all of the above" strategy for motor vehicles.

Recommendations

1. Emphatic public support by the U.S. government for fuel cell electric vehicle (FCEV) deployment will give public and private stakeholders confidence and increase public awareness at a critical point in the commercialization cycle.

2. The U.S. government has an opportunity to work with infrastructure initiatives in Germany, Japan, Korea, the United Kingdom and elsewhere to collaborate on technical and regulatory issues and coordinate rollout plans; doing so would reduce costs and accelerate deployment.

3. Direct DOE investment in hydrogen infrastructure in collaboration with the States and with industry would accelerate deployment in early markets, attract much-needed private investment, and yield valuable experience in achieving a national rollout.

4. These efforts would be most effective if integrated with a well thought-out strategy to support both 2016 and 2025 corporate average fuel economy mileage and greenhouse gas standards recognizing that hydrogen fuel cell vehicles can play an important role by 2025 along with hybrid, battery, biofuels, and improved conventional vehicles.

5. The hydrogen fueling infrastructure build-out should be part of a comprehensive National Energy Policy.

6. DOE's hydrogen and fuel cell research budget has shrunk by more than 50% since FY 2009, while research budgets in other countries have grown significantly; a stronger commitment to research and development would ensure U.S. technology leadership and build on the impressive current U.S. knowledge base.

We base these recommendations in part on our understanding of the worldwide status of hydrogen infrastructure deployment, as summarized below.

Status of Hydrogen Infrastructure

1. **A robust and growing U.S. hydrogen infrastructure exists in the U.S. today.**
   A substantial and growing nationwide hydrogen generation, transport and storage infrastructure exists today that safely and cost-effectively serves industrial demand from refineries, utilities and high-tech manufacturing. U.S. merchant hydrogen production is expected to grow by 40% between 2011 and 2016.

2. **Hydrogen is in use today as an energy carrier.**
   Well more than 200 hydrogen vehicle fueling stations operate worldwide. Hydrogen is used to fuel backup power systems at thousands of communications facilities and other customers. Average Americans use hydrogen every day at work to fuel forklift trucks. The number of hydrogen fills at these and similar facilities is informally estimated to exceed 1,000,000 per year.

3. **Major motor vehicle manufacturers are committed to commercialization in 2015.**
   Hyundai has begun series production and made sales in Europe, with a target of 1,000 sales by 2015. Honda and Toyota are committed to initial production in 2015. Daimler has announced a 2017 commercialization date with an initial production goal of 100,000 vehicles to be delivered over 5 years. General Motors has an ambitious product development effort. Several strong research collaborations have been announced this year, including: Daimler, Nissan and Ford; Honda and GM; BMW and Toyota; and Volkswagen and Ballard, the fuel cell company.

4. **FCEVs, along with other advanced technologies, can deliver energy and environmental security.**
   Numerous recent evaluations by the National Research Council of the National Academies, Universities, and by other respected analysts in the US, Europe and Asia, support the conclusion that a successful and profitable market for electric drive light duty transportation is possible by 2020-2025 with increasing market share to 2050, assuming the right combination of incentives and supportive policies. Analysts see a place for both battery EVs (lower range, smaller vehicles, shorter trips) and hydrogen FCEVs (longer range, heavier vehicles, longer trips). This transition would reduce the need for imported oil in the short term, and by allowing a shift from fossil fuel combustion, and in the longer term has the potential remove the vehicle fleet from the pollution equation.

5. **Research budgets are on the rise in Europe and Asia.**
   The U.S. has historically had a clear lead in research spending on fuel cells and hydrogen energy, but a combination of reductions at home and increases abroad has shifted the leadership. The European Union intends to spend €700 million over the next 7 years, a 40% increase. Japan's fuel cell spending doubled year over year in 2013 to $400 million. The U.K., France and China have also increased their commitments.

6. **Infrastructure is being deployed with support from governments and the private sector.**
   Japan's target is 100 stations by the end of 2015, supported by more than $120 million from the government, and matched by a consortium of oil companies and hydrogen providers. H2Mobility, a European private sector consortium, has set a target for Germany of 100 stations by 2017 and up to 400 stations by 2023, with a budget of nearly $475 million; the German Government has been asked to contribute $100 million. Korea plans 43 stations by 2015 and more than 150 by 2020. A hydrogen station network is in the planning phase in the U.K. and already in place in Scandinavia, where Hyundai cars are in showrooms,

7. **The U.S. lags overall, but California has a strong fueling station program.** California reaffirmed its support for commercializing FCEVs in 2013, when it set aside a revenue stream of up to $20 million per year for the next five years, to build hydrogen infrastructure. These funds are in addition to about $40 million invested to date. There are nine public stations in California today with 19 more in development. Outside California there is not a single truly public fueling station, although there have been recent pledges from governors in the Northeast States, Oregon and Washington, to adopt supportive policies.

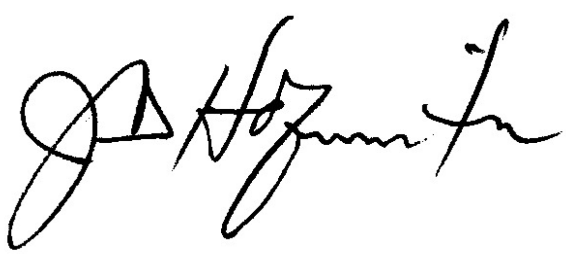
8. **The benefits of DOE activism outweigh the costs.** An analysis by David Greene of Oak Ridge National Laboratory for the International Council on Clean Transportation and further confirmed by the National Research Council calculates that the social benefits of a transition to electric drive outweigh the costs by about 10 to one, an excellent return on the taxpayer's investment. Furthermore, the private benefits are also estimated to exceed the costs by 10 to 1 and have the potential to save consumers billions of dollars in avoided fuel expenditures.

9. **Commercialization is at a critical stage.**
   The transition to FCEVs is already beginning around the world. If the U.S. is to be prepared for a national market for fuel cells, now is the time to step up with a supportive public posture, an increase in funding for research, development and demonstration, and a commitment to some form of risk sharing in support of early infrastructure deployment.

The transition to FCEVs carries risks and uncertainties but holds great promise for reducing fossil fuel use and pollution. DOE has been willing to carry these risks elsewhere in its portfolio where pubic necessity and economic benefits justify it. Leadership and vision can mitigate some of the risks, as can shared financing. If we are successful, the rewards will be substantial.

We hope these recommendations are useful to you as you develop your strategy and budget for 2015 and beyond.

Sincerely,



John D. Hofmeister

Chair

The Secretary of Energy
Washington, DC 20585

March 21, 2014

Mr. John D. Hofmeister
Chair, Hydrogen and Fuel Cell Technical Advisory Committee
U.S. Department of Energy
1302 Waugh Drive, #940
Houston, Texas 77019

Dear Mr. ~~Hofmeister~~ John:

Thank you for your letter regarding hydrogen and fuel cells. The Department values the input of the Committee and appreciates these recommendations as well as the points provided on the status of hydrogen infrastructure.

We agree that public support of hydrogen and fuel cells has significant impact on public and private stakeholder confidence. In fact, we have recently made efforts to increase the visibility of the Department's fuel cell activities, including my December 2013 announcement of $7 million in funding for four fuel cell and hydrogen infrastructure-related projects; our recent activities publicizing the patents, commercial technologies in the market, and emerging technologies that have resulted from the Department's efforts; launching the online Energy 101 resource with a session on fuel cells; and my participation at the Washington Auto Show, where major manufacturers showcased fuel cell vehicles. These types of activities are essential to garnering public interest in hydrogen and fuel cell technologies and demonstrate the Department's support in a public-facing venue.

As for your recommendation on infrastructure, I am pleased to reiterate our commitment to H_2USA, the public-private partnership we co-launched with our industry partners in May 2013. We now have 30 partners, including major global automakers, as well as trade associations representing the natural gas industry and the electric drive industry. H_2USA has launched four working groups on the topics of Hydrogen Fueling Stations, Market Support and Acceleration, Financial Investment, and Locations Roadmap that will address many of the recommendations you raised.

In addition, to address your points on the importance of leveraging international efforts, we participate in the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE), which includes 17 member countries and the European Commission. As you may be aware, Japan recently took over as Chair of IPHE, and the U.S. is now serving as Vice Chair along with Germany. Our recent commitment as Vice Chair

underscores the Department's support of hydrogen and fuel cells, and enables a stronger position for the U.S. in ensuring domestic leadership in this emerging technology area. The activities of H_2USA, IPHE, your own Committee, and other stakeholder input will help provide feedback towards a viable strategy for hydrogen and fuel cells.
I also welcome the Committee's continued engagement as we prepare the interagency Quadrennial Technology Review (QTR) and Quadrennial Energy Review (QER). The QTR lays out a longer-term strategic agenda to help integrate energy research and development programs. The newly launched QER will start by focusing on the development of a comprehensive strategy for the infrastructure involved in transporting, transmitting, and delivering energy. The QTR and the QER will be developed through robust interagency dialogue and engagement of external stakeholders, and develop a framework for national progress toward greater energy and climate security. We would appreciate input from the Committee in these areas as relevant.

Finally, in terms of the Department's budgets for hydrogen and fuel cells, we continue to focus on activities that will yield technology advancements in key areas, including ongoing reductions in the cost and improvement in the durability of fuel cells; reductions in the cost of renewably produced hydrogen; and improvements in systems for storing hydrogen. The President's fiscal year (FY) 2014 budget request for our Fuel Cell Technologies Office was 25 percent higher than the FY 2013 request ($100 million vs. $80 million, with a final enacted amount of $92.9 million). The President's FY 2015 request maintains a high level of support for the office at the FY 2014 enacted level. This is consistent with the Administration's all-of-the above energy strategy, and our activities are aligned with automakers' stated plans for commercial fuel cell vehicles in the 2015 timeframe and beyond.

Recognizing that fuel cell vehicle commercialization is approaching, the Department will continue to closely monitor and evaluate technology status and market potential, and sustain a balanced portfolio of high-impact investments that will include fuel cells and hydrogen as a critical part of the investment mix.

The Department values the Committee's advice and its updates on the status on hydrogen and fuel cell technologies, and looks forward to the Committee's continued reports. Through engagement with stakeholders, including the Committee, we hope to improve the Department's activities in support of these technologies. Please extend my gratitude to the Committee for its insightful and valuable contributions to the Department.

Sincerely,

Ernest J. Moniz

The Hydrogen and Fuel Cell Technical Advisory Committee

Washington, D.C.

June 22, 2014

The Honorable Dr. Ernest Moniz
Secretary of Energy
U.S. Department of Energy
1000 Independence Ave. SW
Washington, D.C. 20585

Dear Mr. Secretary:

Enclosed is the Hydrogen and Fuel Cell Technical Advisory Committee's (HTAC's) Annual Report on Hydrogen and Fuel Cell Commercialization and Technical Development. I am pleased to provide it to you on behalf of my fellow Committee Members, who have endeavored to provide you with a comprehensive, thematic report, along with sufficient detail to create an understandable overview while also writing an easy-to-read document for the widest possible audience.

The Committee is once again pleased to report to you that the working relationship with the Fuel Cell Technologies Office is productive, functional, and cooperative. The Office remains critical to addressing the Department's ongoing efforts on fuel cell durability, costs, advanced research and manufacturing, codes and standards, and infrastructure. The Committee continues to assess these efforts with an ongoing topical subcommittee structure that operates in the mutual interests of both the full Committee and the Program Office.

This Annual Report highlights progress made, as well as challenges, regarding hydrogen commercialization and technical development. It describes both domestic and international developments. It also signals a fundamental conundrum: sustained low levels of Department of Energy funding have slowed progress, and this slow progress negatively impacts market-based funding. The Committee is deeply concerned that increased international support and funding will de-position U.S. leadership, and without increased budgetary support, the United States will fail to demonstrate the priority and progress the Program deserves.

For clarity, this letter includes highlights and concerns captured in the Annual Report that warrant your attention. We conclude with several recommendations for your consideration. We also hope that you have the opportunity to look more closely at the Annual Report itself and that you will enjoy doing so.

Highlights:

- Increasing penetration of stationary fuel cell deployments for back-up power, grid security, and expansion of distributed generation capacity.
- More definitive plans by automobile manufacturers for 2014–2017 commercial deliveries of fuel cell electric vehicles (FCEVs).

- Continued commitment to refueling infrastructure in California.
- Establishment and growth of H2USA.
- Rapid growth in fuel cells for material handling applications.
- Key decisions on policy and regulations, and additional work on codes and standards.
- Some improvement in the financial climate for stationary products amidst weakness for early-stage and venture capital-backed investments.
- Demonstration of hydrogen generation using a variety of renewable resources.

Concerns:

- Decreased funding for fuel cell and hydrogen research and development.
- Stalled progress toward reaching DOE's own goals set in prior years, due to a lack of funding.
- Delays in achieving both cost and durability targets for automotive fuel cells.
- Difficulty in making progress towards cost reduction targets for hydrogen dispensing.
- Diminished progress in hydrogen storage in pressurized tanks.
- A sustained lack of understanding of hydrogen and fuel cell technologies and applications among stakeholders.
- Multiple years of zero budgeting for the education and communication about hydrogen and fuel cell technology.

The Committee provides recommendations in fulfillment of its Congressional mandate as a part of the Annual Report process. The strength of the recommendations' wording reflects the depth of concern felt by the Committee members, emboldened by the promise and enthusiasm we see and feel with regard to the Program's potential contribution to the Department's opportunities to impact the nation's energy future. We welcome the opportunity to discuss these suggestions with you and/or your designate.

Recommendations:

- With respect to both the highlights and concerns, the Committee suggests that the priority and future funding levels for hydrogen and fuel cell technology be increased. Increased funding is critical to progress for commercialization, research and development, infrastructure, and education, and it makes a statement about the fuel cell and technology future to the marketplace and potential investors. FCEVs and stationary fuel cells both contribute to the reliability and security of the nation's future energy system. From the Committee's perspective, we cannot achieve the potential or promise of hydrogen and fuel cell technology in the U.S. energy system at the current priority and funding levels in a time frame that is meaningful, internationally competitive, or serves the nation's interests and defends against potential threats. We know and understand the priority preference that has been demonstrated within the Department as regards battery electric vehicles (BEVs). We are aware of both the progress and near-term successes of the Program, as well as some of its challenges and difficulties. We thus recommend more priority and emphasis on FCEVs in an "all of the above" world for the fundamental reason that future outcomes will be "no regrets" for doing so.

- We would be pleased if you would request a review of the HTAC's work later this year or early next year as we approach the ten-year anniversary of the Committee's formation and commissioning. The Committee has not yet had the opportunity to present its work, worth, and accomplishments to the Secretary in person. We welcome an opportunity in which both you and members of your leadership team can hear and see firsthand how this Committee of energy technology and public policy expert volunteers is committed to helping shape a part of the nation's future energy system in support of the ongoing efforts of the Department and its Program Office.

We look forward to continuing our service to you, your leadership team, and the Program Office. It is a pleasure for us to serve the nation with our contributions and to serve on this Committee. Any feedback you might have would be most welcome and appreciated.

Sincerely yours,

John Hofmeister
Chair
On behalf of the Hydrogen and Fuel Cell Technical Advisory Committee

2013 ANNUAL REPORT of The Hydrogen and Fuel Cell Technical Advisory Committee

Hydrogen and Fuel Cell Technical Development and Commercialization Activity

Summary

Hydrogen and fuel cells offer numerous economic, environmental, and energy-security benefits and are being developed for use in a variety of industrial, residential, transportation, and utility applications. Hydrogen is an energy-dense fuel that can be generated from a variety of resources, including renewables, thereby addressing energy security and sustainability challenges that face our nation. Fuel cells are energy efficient, clean, and fuel-flexible, and could replace internal combustion engines in vehicles and provide power for stationary and portable power applications. Despite these very attractive attributes and the substantial commercial and technical accomplishments in 2013, the widespread deployment of hydrogen fuel and fuel cells still presents some significant challenges.

This Annual Report of the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) highlights worldwide advancements and challenges with regard to hydrogen and fuel cell commercialization, policy, regulation and code developments, financial climate, and research and development (R&D) during 2013. Among the important achievements during the year, the HTAC considers the following noteworthy:

- There has been significant growth in the deployment of fuel cells in stationary applications (including large power parks, small-scale combined heat and power (CHP), and back-up power) as well as material handling applications. That growth, and the perception that profitability is in sight, has prompted financial markets to drive up stock prices for a number of the key participants.
- Several major automobile manufacturers announced definitive plans to introduce fuel cell electric vehicles (FCEVs) into the market in the 2014–2017 time frame. Four substantial FCEV development partnerships (Toyota/BMW, Honda/GM, Daimler/Ford/Nissan, and Volkswagen/Ballard) were announced during the year. These signals from the automobile manufacturers led to financial and organizational commitments from several countries to increase R&D support and accelerate infrastructure deployment. For example, in the United States, California made a large multi-year financial commitment to infrastructure and a public-private partnership, H2USA, was formed.
- The generation of hydrogen using a variety of renewable resources has been successfully demonstrated and a number of substantial "power-to-gas" (P2G) projects have been launched in Europe.
- A number of important policy and regulatory decisions, particularly in the United States, will help to smooth the pathway to more rapid growth of the hydrogen and fuel cell industry. Nevertheless, implementation may still take time and some critical hurdles remain.

Commercialization Initiatives

All segments of the hydrogen and fuel cell industry enjoyed significant commercial activity in 2013, with a substantial portion of the activity occurring outside of the United States.

Fuel Cells for Stationary Applications: Fuel cells for distributed power continued to dominate the market in 2013, with 80 percent of total fuel cell units manufactured and megawatts shipped in stationary markets.

- In Japan, the Ene-Farm deployment, a heavily subsidized government-sponsored program started in 2009, helped developers install more than 25,000 residential fuel cell CHP systems, bringing the total deployed to more than 65,000. These systems can be fueled by natural gas, propane, or town gas, and reportedly achieve overall energy efficiencies as great as 95 percent. The Japanese government's new draft energy strategy calls for more than 5 million units to be installed by 2030.
- In Korea, natural gas-powered fuel cell capabilities expanded, in large part through a partnership and licensing agreement between U.S.-based FuelCell Energy (FCE) and POSCO Energy, an independent power producer owned by POSCO, South Korea's largest steel producer.
  - POSCO Energy began construction of a fuel cell manufacturing facility expected to produce at an initial fuel cell capacity of 100 megawatts (MW) per year in 2015.

- POSCO's Gyeonggi Green Energy park had 16 operational 3-MW FCE fuel cells by late 2013.
- Korea Hydro and Nuclear Power installed the first stage (20 MW) of a 120 MW fuel cell power plant, located on a former municipal landfill that has been converted to a renewable energy park.

■ The United States and Canada expanded commercial deployment of natural gas powered fuel cells.

- Bloom Energy announced the installation of 50 MW of solid oxide fuel cells (SOFC) at a number of well-known corporations, including a 27 MW installation for Delmarva Power in Delaware. Bloom Energy now has systems totaling more than 100 MW installed in the United States, and completed its first international installation in late 2013 at SoftBank's M-Tower in Fukuoka, Japan.
- FCE completed a 14.9 MW fuel cell park in Bridgeport, Connecticut, consisting of five fuel cell power plants and an organic rankine cycle turbine as a bottoming cycle. The project is located on a remediated brownfield site in an industrial area, and is under a 15-year agreement with Connecticut Light & Power. FCE also completed installation of a 1.4 MW fuel cell at California State University, San Bernardino.
- ClearEdge Power expanded its product line to include a 400 kilowatt (kW) phosphoric acid fuel cell system acquired through its purchase of UTC Power. ClearEdge announced that its 400kW stationary fuel cells have reached a total of 1,000,000 hours of field operation.
- Ballard Power commissioned a 1 MW proton exchange membrane fuel cell (PEMFC) ClearGen™ system at the headquarters of Toyota USA at the end of 2012. It also announced the sale of a 175 kW ClearGen™ system to Azure Hydrogen, its Chinese partner, as a possible prelude to expansion into China and across Asia.
- FuelCell Energy, which is operating a waste-to-energy demonstration in Fountain Valley, California (Figure 1), reached agreement to demonstrate a comparable "tri-generation" power plant to provide electricity, heat, and renewable hydrogen. The heat will be supplied to Village Farms of Vancouver, British Columbia, a hydroponic greenhouse business, while the renewable hydrogen will be exported for vehicle fueling or industrial applications. The system is expected to be operational in early 2014.

Figure 1. Hydrogen fueling station at the Orange County Sanitation District's municipal wastewater treatment facility in Fountain Valley, CA. *Photo courtesy of Air Products and Chemicals, Inc.*

Fuel Cells for Transportation Applications: Global automobile manufacturers continued making major progress toward the commercialization of passenger cars equipped with PEMFC technologies for motive power.

■ Honda, Toyota, and Hyundai all confirmed plans to introduce production vehicles in 2014 (Hyundai) or 2015 in Korea, Japan, Northern Europe, and California. Initial sales volumes are expected to be modest.

- Honda and Toyota unveiled new fuel cell concept vehicles at auto shows in 2013 (see Figures 2a and 2b).
- Hyundai announced it would produce 1,000 fuel cell vehicles on the Tucson platform, and had shipped a number to Denmark during 2013.

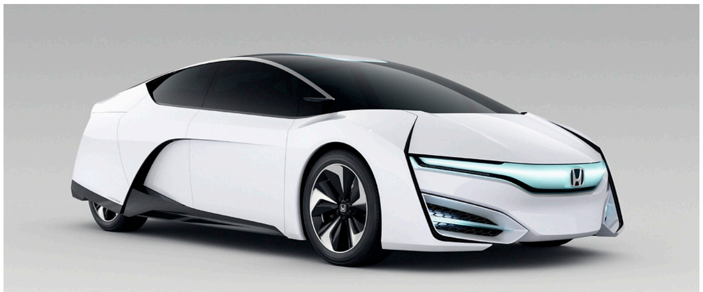


Figure 2a. Honda fuel cell electric vehicle concept car 2013. *Photo courtesy of Honda Motor Company.*

■ Three OEM collaborations (Toyota-BMW, Daimler-Ford-Nissan and Honda-GM) and one technology access agreement (Volkswagon-Ballard) were established. The collaborations are intended to share intellectual property, mitigate technological risk, share development costs, promote innovation, and accelerate development and achievement of manufacturing scale

Figure 2b. Toyota fuel cell electric vehicle concept car 2013.
Photo courtesy of Toyota Motor Corporation.

economies through shared designs. In announcing its collaboration with Nissan and Ford, Daimler delayed its plans to produce vehicles for Germany and other markets until 2017.

- Although OEMs are reluctant to divulge costs, there are signals that key performance metrics such as power density, range, refueling time, and cold operation are sufficient to justify commercial deployment. Regarding costs, statements from the OEMs suggest that the fuel cell system cost for an 80kW system, based on high-volume manufacturing (500,000 units per year), is reasonably consistent with the U.S. Department of Energy's (DOE's) current modeled cost of $55/kW, shown in Figure 3. Second generation technology is expected to continue progress toward 2020 cost targets.
- OEMs continue to accumulate durability and practical field fleet experience with earlier generation vehicles.
  - General Motors announced that its fuel cell vehicle fleet, originally launched in 2007 as Project Driveway, is approaching 3 million miles of real-world driving. Individual vehicles have accumulated more than 100,000 miles. The first vehicle to cross this milestone is shown in Figure 4.
  - Hyundai announced its development fleet has accumulated 2 million miles of driving.
  - Mercedes-Benz announced that its global F-Cell fleet had achieved 1 million miles of driving by the third quarter of 2013.
- Progress is also being made on fuel cell applications in buses and other specialty vehicles.
  - The Federal Transit Administration's National Fuel Cell Bus Program awarded $13.6 million for eight projects focused on advancing the commercialization of U.S.-made fuel cell buses. At the turn of the year, it issued a call for proposals under its Low or No Emission Vehicle Deployment Program; at least $24.9 M is available for fuel cell and other advanced buses.
  - The University of Delaware announced plans to add two new fuel cell buses to increase its fleet to four. Golden Gate Transit will operate one bus as part of Zero Emission Bay Area (ZEBA).

Figure 4. GM Equinox 100,000-mile fuel cell electric vehicle.
Photo courtesy of General Motors Corporation.

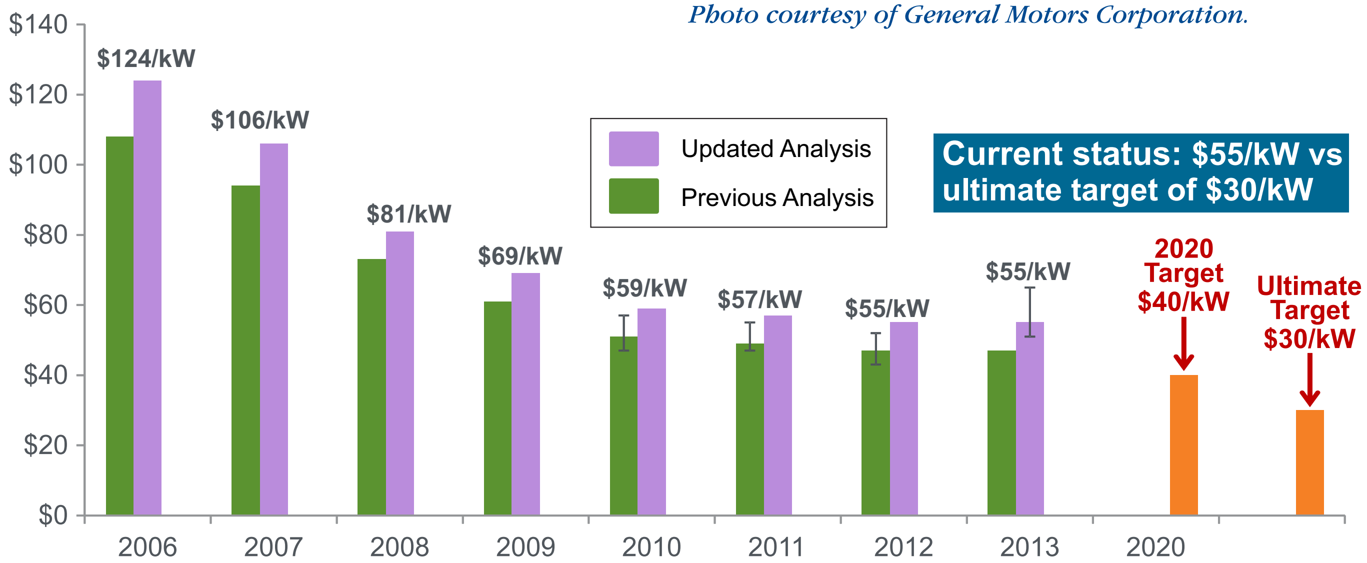


Figure 3. Modeled fuel cell cost progression for 80 kW automotive system at a projected high-volume production rate of 500,000 units per year. *Source: U.S. Department of Energy, Fuel Cell Technologies Office.*

- CTTransit and the Center for Transportation and the Environment (CTE) finalized a deal to deliver the first commercially procured fuel cell bus under a standard Request for Proposal (RFP) process. The bus will use a Ballard FCvelocity®–HD6 fuel cell and a BAE Systems HybriDrive propulsion system.
- US Hybrid agreed with UTC to license its fuel cell system for buses and possibly other heavy-duty vehicle applications.

- Internationally, there has been considerable activity in the fuel cell bus market.
  - Van Hool NV and the Transit Authority in Aberdeen, Scotland, will deploy 10 fuel cell buses powered by a Ballard FCvelocity–HD6 fuel cell module.
  - Ballard signed a non-binding Memorandum of Understanding and a multi-year agreement with its partner Azure Hydrogen Corporation to support Azure Hydrogen's fuel cell bus program for China.
  - Tata Motors conducted test runs of India's first hydrogen fuel cell-powered bus.
  - The Karlsruhe Institute of Technology (KIT) in Germany started shuttle service between its campuses using two Mercedes-Benz Citaro FuelCELL Hybrid fuel cell buses.
  - BC transit in Canada went against the trend, shutting down its 20-bus fuel cell fleet in December of 2013 at the end of a 5-year trial.
- Demonstrations in the United States and Taiwan were highlights for the specialty vehicles area.
  - In 2013, DOE launched field demonstrations for fuel cells in delivery vans, airport equipment, and refrigerated shipping containers.
  - In Taiwan, a demonstration of 80 fuel cell scooters from Asia Pacific Fuel Cell Technologies was completed with more than 150,000 miles driven. The units were made available for regular rental and attracted more than 10,000 users.

Fuel Cells for Materials Handling: The U.S. materials handling market has been a growth sector for fuel cells, with hydrogen-powered fuel cell forklift fleets operating in warehouses, distribution centers, and manufacturing facilities for major companies including BMW, Coca-Cola, Fed-Ex, and Wal-Mart.

- According to Fuel Cells 2000, more than 4,000 fuel cell forklifts are in use in the U.S. today.
  - Plug Power in Latham, New York currently has an 85 percent market share, but other companies are growing as firms in the United States and Europe introduce fuel cell lift trucks in their warehouses.
  - During the year, Plug Power introduced a new 14kW GenDrive® 1900 PEM fuel cell system for materials handling applications. With two on-board 350 bar hydrogen storage tanks holding 3.5 kg of gas, the large Class 1 fork lifts using the GenDrive 1900 will run continuously for eight hours.
  - Under the DOE American Recovery and Reinvestment Act of 2009 (ARRA) program, 490 forklifts were deployed with approximately 98 percent reliability over 2 million hours of operation and 300,000 hydrogen fills between 2009 and 2013.

Fuel Cells for Back-up Power Applications: Fuel cells are generally regarded as superior to diesel back-up generators in many ways, including greater reliability, lower emissions, better energy efficiency, and ready installation. Reliable back-up is especially important during natural disasters, to power critical infrastructure such as cell networks for communications, power for hospitals, and logistics for food and water supplies. Following Hurricane Sandy in 2012, ClearEdge Power PureCell® fuel cells at Price Chopper supermarkets in Colonie, New York, and Middletown, Connecticut, operated without the grid for five and six days, respectively, allowing these establishments to continue critical operations and keep food available for the public.

- Fuel cell systems have been installed in a number of hospitals to provide back-up power.
  - At St. Francis Hospital in Hartford, Connecticut, two 400-kW ClearEdge fuel cell systems back up the operating room and provide half the building's electrical needs.
  - Installations completed or planned include FCE systems at Stamford Hospital (4.8 MW) and Waterbury Hospital (2.4 MW) in Connecticut, and a ClearEdge system at St. Helena Hospital (400 kW) and a Bloom Energy system at Sutter Santa Rosa Hospital (600 kW), both in California.
- Ballard Power has reached the 500-unit milestone on shipments of methanol-fueled back-up power units for telecom applications; 215 of these ElectraGen™ units were produced at its plant in Mexico during the first quarter of 2013.
- A 6MW Bloom Energy system was turned on in September 2013 to power 30 servers at an eBay data center in Salt Lake City.

- Late in the year, Ceramic Fuel Cells Ltd. reported an order from Synergy International in Estonia for 1000 BlueGen™ solid oxide systems over the next two years.

- Fuel cell backup power systems are in operation for China Mobile, China Unicom, and China Telecom, the three main mobile phone network operators in China.

Hydrogen for Grid Support Applications: Electrolyzers are being evaluated for use in grid balancing systems to help smooth out generation from wind turbines and solar systems. These systems would provide a load when grid demand is low and renewable power sources are available, and in some cases provide hydrogen to fuel conventional generators when renewable power is not available. This type of grid support is increasingly necessary as the percentage of intermittent renewable generation on electric grids increases.

- Approximately 30 P2G projects have been launched in Europe, in response to the growing amount of renewable generation connected to national power grids.

- Several companies announced major hydrogen energy storage projects and plans.
  - Eleven companies established the North Sea Power to Gas Platform to develop technology for the conversion of renewable power into hydrogen via electrolysis.
  - Hydrogenics Corporation and eight partners are collaborating on a 5-year energy storage research, development and demonstration project in Belgium.
  - Hydrogenics and E.ON launched commercial operation of its P2G facility in Falkenhagen, Germany (see Figure 5). Hydrogenics will also install a 1-MW hydrogen energy storage system in Hamburg, Germany.
  - ITM Power won a competitive tender process to supply a 360kW P2G energy storage plant for a Thüga Group project, the company's first major commercial sale of a large hydrogen production unit in Germany.
  - The Hydrogen Mini Grid System (HMGS) in Rotherham, UK, operated by ITM Power, will convert wind power to hydrogen for vehicle fuel and backup power generation.
  - ITM Power was also awarded a €350,000 (US$463,000) grant to work with a consortium on the CommONEnergy project funded under the EU's Seventh Framework Program. The project will demonstrate energy-efficient technologies and energy storage solutions for non-residential buildings.

Figure 5. Hydrogenics P2G facility in Falkenhagen, Germany.
Photo courtesy of Hydrogenics.

  - Acta S.P.A signed a Letter of Intent with Ecoisland Partnership to run a domestic renewable energy storage trial project for a house on the Isle of Wight, for which Acta S.P.A will provide an electrolyzer and hydrogen storage tanks.

Hydrogen Infrastructure: Although the worldwide hydrogen fueling infrastructure is still in its infancy, this year saw significant new commitments of financing for stations. The number of fully operational hydrogen fueling stations globally exceeded 220 in 2013, though many are not open to the public (Figure 6 shows a typical station).

- As signals from the auto industry began to make it clear that the vehicles are coming, infrastructure activities in Japan, Germany, and California accelerated and focused on public accessibility.
  - In Japan, where 17 demonstration stations are operating, the government agreed to support 100 stations, in partnership with Japanese oil and hydrogen companies. The government committed $46 million in 2013 with another $72 million anticipated in 2014 for a network of stations across southern Japan. The first 19 of the new-generation commercial stations were announced late in 2013.
  - In Germany, the H_2 Mobility initiative announced a plan to expand the current network of 15 stations to 100 public hydrogen stations in the next four years and to 400 stations by 2023, with a $463 million investment from as-yet unidentified sources.

Figure 6. Hydrogen fuel dispenser in Torrance, CA. *Photo courtesy of National Renewable Energy Laboratory.*

    - In California, new legislation (AB8) provides up to a $20 million per year commitment to fund hydrogen fueling stations until there are at least 100 public stations. After awarding $12 million to support seven stations early in 2013, the California Energy Commission made available $29.9 million late in the year for another round of stations.

- Several initiatives aimed at coordinated planning for infrastructure roll-out launched this year.
    - H2USA, a public-private partnership focused on supporting the build-out of hydrogen fueling infrastructure, formed in the spring. During the year, H2USA held organizing meetings and began fundraising.
    - Twenty corporate partners established Mobilité Hydrogene France to support a public-private infrastructure deployment plan in France.
    - UK H_2Mobility expanded its operations and new partner involvement to include the Greater London Authority, the Welsh Government, and Transport Scotland.
    - H_2Mobility Swiss was established.

- A number of corporate participants announced technical and operational initiatives and results. These include:
    - Air Products and Chemicals Inc., in collaboration with Bennett Pump Company, announced a new consumer-friendly hydrogen dispenser to be installed in 10 stations in California.
    - Linde, in cooperation with Wystrach GMbH, has developed a light-weight 500-bar composite storage tank allowing delivery of 1,100 kg of hydrogen in a single tube trailer.
    - Danish company H2Logic demonstrated it could install a modular fueling station in 48 hours. The station will be used to fuel Hyundai vehicles delivered to Copenhagen.
    - The Toyota Tsusho Corporation and Air Liquide signed a new joint venture to build hydrogen fueling infrastructure in Japan.

As the year drew to a close, a number of infrastructure financing and operational initiatives were percolating, particularly in California where early vehicle roll-outs are anticipated. One Toyota executive commented, "We've seen players we never heard of before suddenly come out of the woodwork." All of which suggests that 2014 and beyond may be a very interesting time for infrastructure development.

Policy, Regulations, Codes and Standards

Codes and Standards: Significant progress was made in 2013 on the development of codes and standards relevant to hydrogen and fuel cells.

- The NFPA2 Hydrogen Technologies Code was referenced in the International Fire Code (IFC), effectively making NFPA2 the U.S. national hydrogen code.
- SAE J2601 Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles was completed.
- NFPA 55 Code for Compressed Gases and Cryogenic Fluids was revised to more clearly address hydrogen storage.
- A new Canadian Standards Association (CSA) standard (ANSI/CSA FC-1) was issued for stationary fuel cells.
- The Global Technical Regulation on hydrogen and fuel cell vehicles was issued.

Despite these developments, many code compliance issues remain.

Policy: International progress on policies supporting hydrogen and fuel cell R&D and deployment continued in 2013, and individual states also launched leadership programs and policies.

- The European Union, Japan, and others made significant new financial commitments for research, demonstration, and infrastructure deployment.
  - Europe's Horizon 2020 program allocated $926 million over seven years for a cost-shared program.
  - Japan's hydrogen and fuel cell R&D budget doubled in 2013 to $400 million.
  - China renewed its alternative-energy vehicle subsidy program to address air quality issues. FCEVs, including buses, qualify under the subsidy for the first time, and will be eligible for an $8,000 rebate.
  - The United Kingdom Office of Low Emission Vehicles launched Driving the Future Today, which outlines the UK's technology-neutral strategy for promoting and adopting ultra-low emission vehicles (ULEVs). The strategy outlines development of a hydrogen fueling infrastructure to support FCEVs, including buses.
- The California Governor's office released the "2013 ZEV Action Plan" that includes a goal to have 1.5 million zero-emission vehicles, including hydrogen fuel cell vehicles, on the road by 2025.
- The New Jersey Economic Development Authority (EDA) and the New Jersey Board of Public Utilities (BPU) launched a second round of the Large Scale Combined Heat and Power/Fuel Cell Program, which supports CHP and stand-alone fuel cell projects with a generating capacity of greater than 1 MW, with up to $3 million available per project.
- Connecticut released its 2013 Comprehensive Energy Strategy, which outlines strategies for meeting its energy needs in a cleaner, more reliable way. To meet the "20% by 2020" renewable portfolio standard, the state will have to increase its Class I resources (fuel cells, solar, and wind) by 3 gigawatts (GW).

Financial Climate

During the course of 2013, there was a major change in the financial climate for hydrogen and fuel cell companies.

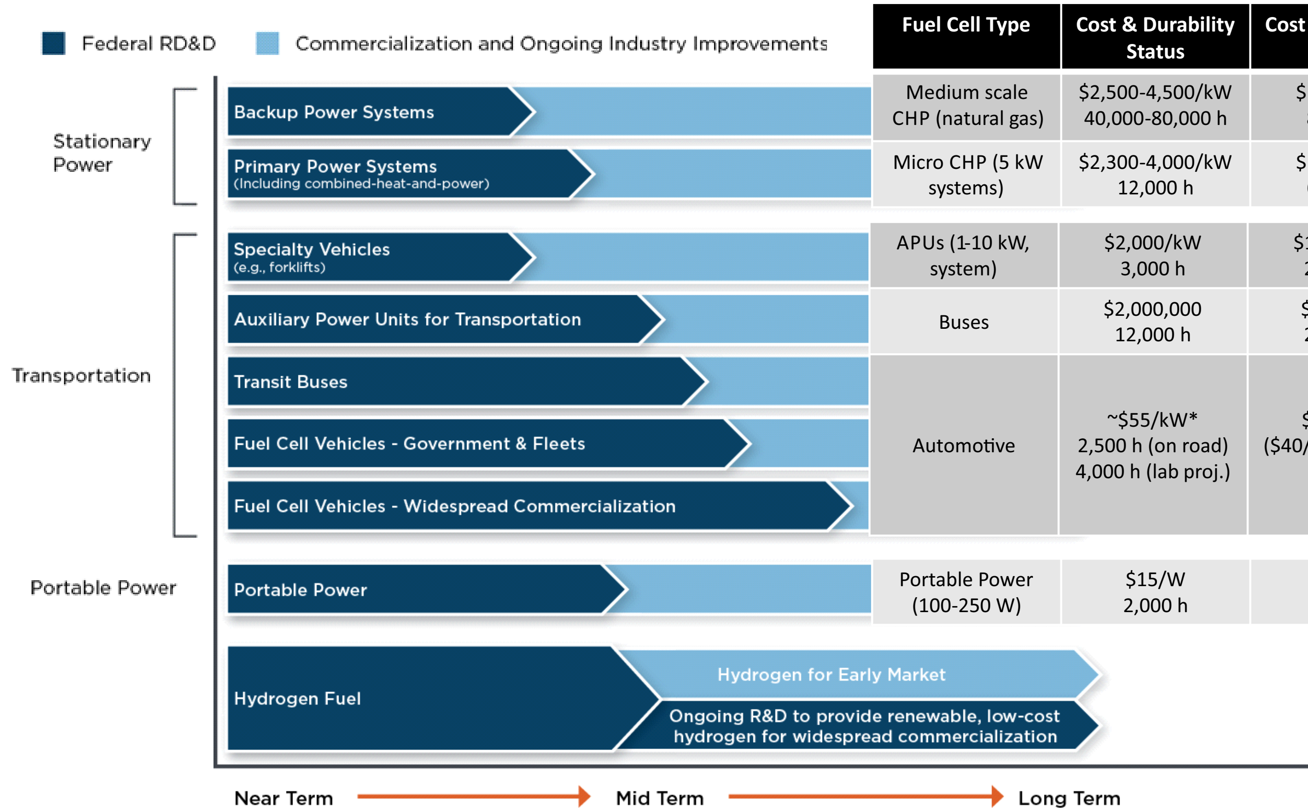
- At the beginning of the year the climate was gloomy.
  - United Technologies completed the sale of its fuel cell assets to ClearEdge Power, but had to sweeten the deal with $48 million in cash. In total, UTC reportedly took a charge of approximately $227 million on the transaction.
  - Hess Oil refocused on its core business and put its Nuvera fuel cell and hydrogen production/dispensing business up for sale; at year-end a deal had yet to be completed.
  - BASF decided to exit its high-temperature fuel cell membrane business, closing its New Jersey operation. The technology was acquired by Advent Energy and moved to Connecticut, with the encouragement of $1 million from Connecticut Innovations.
  - Wartsila spun off its solid oxide fuel cell activities into a new company, Convion Oy.
  - The ambitious Ecoisland Partnership on the Isle of Wight went into voluntary liquidation due to lack of funding, though elements of the project are likely to continue under separate funding arrangements.
- Financial transactions during the early part of the year were done at very modest values.
  - FCE re-acquired the remaining shares of the solid oxide fuel cell company Versa Power Systems, owned by other investors, for $3.3 million.
  - The French company McPhy acquired Italian electrolyzer company PIEL for $13.3 million.
  - Cummins Inc. made a strategic investment in ReliOn, the Spokane-based PEM fuel cell company, for an undisclosed amount.
  - Struggling UK-based solid oxide fuel cell manufacturer Ceres Power signed an agreement with Korean boiler-maker KD Navian.
- Early stage and venture-backed companies often found it very difficult to raise capital and, when they did, the amounts were generally modest and valuations relatively punitive.
  - Point Source Power, a start-up company that had licensed Lawrence Berkeley National Laboratory solid oxide fuel cell technology, was unable to complete a modest crowd source funding effort.
  - ACAL Energy, a UK company, raised bridge financing from existing investors but its efforts to raise capital from new investors had not been successful by the end of the year.

- The financial climate in the latter part of the year became more favorable, at least for public fuel cell companies, leading to a number of more attractive deals.
  - Air Liquide made a \$6.5 million structured investment in Plug Power (PLUG), and then late in the year Plug's stock price escalated and continued to rise into 2014, apparently on the strength of large order announcements.
  - Ballard (BLDP), Hydrogenics (HYGS), and Fuel Cell Energy (FCEL) saw significant upward movement in their stock prices and took advantage with secondary stock offerings. The market capitalization of all these companies, though materially improved, remained at a small fraction of invested capital and stock prices were still far short of the values at the time of their initial public offerings more than a decade ago.

A bright spot in the financial picture was Bloom Energy, a company commercializing solid oxide fuel cells. While the rest of the hydrogen fuel cell market struggled, Bloom raised an additional \$130 million, bringing its total invested capital to a reported \$1.1 billion. The company also signed a major joint venture with Japanese telecom/internet giant SoftBank Group. Bloom is reportedly considering a public offering, which, if successful, could well pull the rest of the companies in the industry up with it.

Research and Development

Research and development activities provide important support for efforts to commercialize hydrogen fuel and fuel cells. Some advances are being made towards meeting key targets established by DOE, despite relatively low funding levels for the DOE fuel cell program in recent years. The current status against DOE cost and durability targets for fuel cells is illustrated in Figure 7, while projected high volume hydrogen production costs are illustrated in Figure 8. A number of metrics can be



Fuel Cell Type	Cost & Durability Status	Cost & Durability Target
Medium scale CHP (natural gas)	\$2,500-4,500/kW 40,000-80,000 h	\$1,000/kW 80,000 h
Micro CHP (5 kW systems)	\$2,300-4,000/kW 12,000 h	\$1,500/kW 60,000 h
APUs (1-10 kW, system)	\$2,000/kW 3,000 h	\$1,000/kW 20,000 h
Buses	\$2,000,000 12,000 h	\$600,000 25,000 h
Automotive	~\$55/kW* 2,500 h (on road) 4,000 h (lab proj.)	\$30/kW* (\$40/kW by 2020) 5,000 h
Portable Power (100-250 W)	\$15/W 2,000 h	\$5/W 5,000 h

Figure 7: Department of Energy cost and durability status and targets for fuel cells.
Source: U.S. Department of Energy, Fuel Cell Technologies Office.

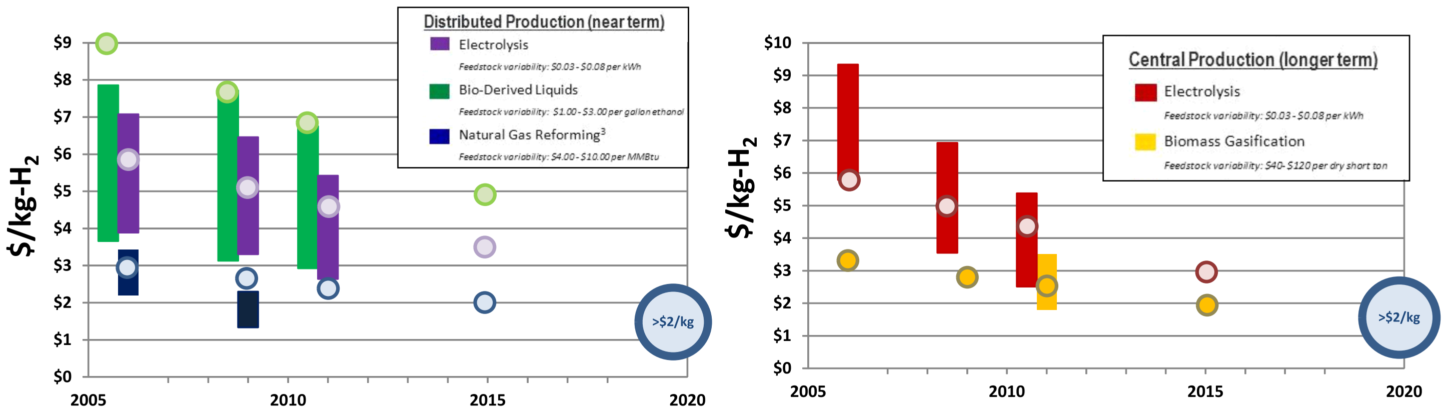


Figure 8: Predicted high-volume hydrogen production costs via distributed and central production (status in vertical bars, targets in circles, 2007 dollars).

Source: U.S. Department of Energy, Fuel Cell Technologies Office Program Record #14011, Hydrogen Cost Target Calculation, June 2014, http://www.hydrogen.energy.gov/pdfs/14011_h2_cost_target_calculation.pdf.

used to assess progress in R&D, including patents and publications.

- After many years of leading clean technology innovation, the number of patents issued for fuel cell technologies dropped slightly in 2013.
  - The top five companies for fuel cell patents were GM, Honda, Toyota, Samsung, and UTC Power (now ClearEdge).
  - There is speculation that the decline in issued patents for fuel cell technologies is a consequence of decreased DOE investment in fuel cell and hydrogen R&D. As illustrated in Figure 9, DOE funding for 2013 was down from levels in 2012 and was substantially below the high point in 2007 of almost $330 million in funding provided under the DOE Hydrogen Fuel Initiative, including $63.4 million in the Solid State Energy Conversion Alliance (SECA) Program. Conversely, the European Union, Japan, and California made significant new financial commitments for research, demonstration, and infrastructure deployment.
- The number of new R&D papers published this year indicates that this field of inquiry is still very robust.
  - More than 260 papers describing the results of fuel cell research and development were published. Topics ranged from new electrocatalytic and membrane materials to advanced cell architectures.
  - With regard to hydrogen production, nearly 860 relevant papers were published describing many new catalytic materials for the conversion of feedstocks including water, hydrocarbons, and biomass.

Continuing Challenges

While deployment of fuel cells in various applications has been increasing, there remain several technical challenges that hinder more widespread acceptance and implementation. There is the continuing challenge of decreased funding for fuel cell and hydrogen R&D, but perhaps more of an issue is that progress toward reaching the goals set by DOE has stalled over the past few years in automotive fuel cells, hydrogen production, hydrogen storage, and stationary power. Of course, it is important to re-evaluate whether the goals remain appropriate; DOE is undertaking such a task, but the following key areas have shown little or no change from their status in 2011:

- The automotive fuel cell cost goal is $30 per kW and the projected cost at 500,000 units per year has remained at approximately $55 per kW since 2010.
- The automotive fuel cell durability goal is 5,000 hours and the status measured in NREL field tests is 2,500 hours, although industry has signaled informally that system tests have demonstrated up to 7,000 hours and ACAL Energy has published single cell performance of more than 10,000 hours.

Funding ($ in thousands)

Office of Energy Efficiency and Renewable Energy	FY 2012	FY 2013		FY 2014		FY 2015
Key Activity	Approp.	Request	Enacted (C.R.)	Request	Enacted	Request
Fuel Cell R&D	43,634	36,899	41,266	37,500	33,383	33,000
Hydrogen Fuel R&D	33,824	26,177	31,682	38,500	36,545	36,283
Manufacturing R&D	1,944	1,939	1,899	4,000	3,000	3,000
Systems Analysis	3,000	2,922	2,838	3,000	3,000	3,000
Technology Validation	8,986	4,992	8,514	6,000	6,000	6,000
Safety, Codes and Standards	6,938	4,921	6,808	7,000	7,000	7,000
Market Transformation	3,000	0	2,838	3,000	3,000	3,000
Education	0	0	0	0	0	0
NREL Site-wide Facilities Support	0	0	0	1,000	1,000	1,700
SBIR/STTR	2,298	2,150	2,139	TBD	TBD	TBD
Total	$103,624	$80,000	$97,984	$100,000	$92,928	$92,983

Funding ($ in millions)

Other DOE Offices	FY2012	FY 2013	FY 2014
Basic Science	27	26	~$25
Fossil Energy, SECA	25	23.8	$25
ARPA-E	2	2	~$30
Total	$54	$52	~$80

Total FY14 Budget: >$172M

Figure 9. Recent Department of Energy funding for hydrogen and fuel cells R&D. *Source: U.S. Department of Energy, Fuel Cell Technologies Office.*

- The hydrogen production cost goal is less than $4 per gasoline gallon equivalent, and the current status is reported by DOE to be $4–9 per gasoline gallon equivalent. Industrial gas companies have indicated in public presentations that hydrogen can be dispensed to the consumer at $8/kg today for a fully loaded 150-200 kg/day station with high-pressure hydrogen delivered by tube trailer from a nearby large-scale production facility. This achieves parity with a 30 miles-per-gallon gasoline vehicle at $4/gasoline gallon. The dispensed price can be as low as $6/kg when hydrogen can be delivered by pipeline from nearby large-scale production facilities, which is equivalent to $3/gasoline gallon.

- Hydrogen storage performance for pressurized tanks remains about 50 percent below the goal of 2.3 kWh per liter or 2.5 kWh per kilogram. Stationary power status on both cost and durability is unchanged from 2011 and remains a factor of 3.5 times more costly than the goal.

- One performance measure that already meets the DOE goal is automotive driving range. While unchanged from 2011, it exceeds the target of more than 300 miles. At least one vehicle OEM reported achieving ranges of more than 400 miles.

A final continuing challenge is the lack of understanding and appreciation of hydrogen and fuel cell technologies and applications among many stakeholders, especially in the early adopter regions. A focused and dedicated explanation of the status and potential for hydrogen and fuel cells is warranted, as infrastructure and market growth will depend upon their acceptance by the public. This lack of awareness and knowledge could jeopardize the early successes and importance of this undertaking.

Reports

A number of reports on hydrogen and fuel cells were published in 2013.

- A report from the Institute of Gas Engineers and Managers in the UK affirms the importance of hydrogen in reducing carbon dioxide emissions and increasing the useful output of renewables.

- “The Business Case for Fuel Cells,” a report prepared by Fuel Cells 2000 with DOE support, summarizes the purchases of fuel cells for stationary (32 MW) and materials handling (1,100) applications in 2012.

- The National Research Council published *Transitions to Alternative Vehicles and Fuels*, a report that examines the current capability and estimated future performance and costs of alternative vehicles and non-petroleum-based fuel technology. The report analyzes scenarios that combine various fuel and vehicle pathways, identifies barriers to implementation, and suggests policies to achieve goals for reducing petroleum use and greenhouse gas emissions.

- The California Fuel Cell Partnership published “A California Road Map,” which details plans for the roll-out of fuel cell buses.

- Navigant Research released a white paper on "The Fuel Cell and Hydrogen Industries: 10 Trends to Watch in 2013 and Beyond."
- UK H_2Mobility published a Phase 1 Report evaluating the potential of FCEVs to "decarbonise road transport, create new economic opportunities, diversify national energy supply, and reduce significantly the local environmental impacts of road transport."
- The HTAC commissioned development of a report on hydrogen and renewables integration.

Conclusions

During 2013, there was significant expansion in the deployment of fuel cells, in particular for stationary and materials handling applications. Of particular note is the successful Ene-Farm deployment in Japan. The fact that automotive companies, in several cases via partnerships, are preparing to offer FCEVs to the public suggests that cost and performance are moving into acceptable ranges. These activities have stimulated the climate for fuel cell financing, encouraged the establishment of new policies and codes, and caused a refocus in R&D investment.

Despite a number of positive signals, challenges remain. Technical progress in key areas has been steady during the past few years, but DOE investments have decreased. Given these recent developments and the substantial but as yet unrealized potential of hydrogen and fuel cell technologies, it is clear that further market development support is needed to assure the continued positive trajectory of commercialization of these systems.

Department of Energy
Washington, DC 20585

August 6, 2014

Mr. John Hofmeister, Chair
Hydrogen and Fuel Cell Technical Advisory Committee
1302 Waugh Dr., #940
Houston, Texas 77019

Dear Chairman Hofmeister,

Thank you for your June 2014 letter to Energy Secretary Moniz and the accompanying *2013 Annual Report of the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC)*. The Department values the input of the Committee and appreciates this thorough and detailed report on the status of hydrogen and fuel cells.

We agree that it is a critical time to establish a U.S. leadership position in the development, commercialization, and manufacture of hydrogen and fuel cell technologies. We continue to monitor global developments through the International Partnership for Hydrogen and Fuel Cells in the Economy, an international partnership of seventeen countries and the European Commission, as well as through direct contact with our equivalent agencies in countries such as Germany and Japan. Our activities within the Department are paving the way for global competitiveness with more than 450 patents, 40 commercial technologies in the market, and 65 emerging technologies anticipated to be in the market in 3 to 5 years – all as a direct result of our funding and strategic efforts.

In terms of funding, we continue to support the President's "all of the above" energy strategy by maintaining a consistent and substantial budget for hydrogen and fuel cell technologies. The Fiscal Year (FY) 2015 budget request is approximately $93 million, which is consistent with both FY2013 and FY2014 levels.

The Department values the advice and commitment of the Committee in its efforts to continue to improve the Department's programs and activities related to hydrogen and fuel cells. In response to your request for a formal review of HTAC, this is not necessary given the role of a federal advisory committee to provide advice to the Department. However, further engagement with the Committee may be solicited in the coming year to strengthen coordination with our senior leadership. In particular, Reuben Sarkar, the Deputy Assistant Secretary for Sustainable Transportation is anticipated to engage with the Committee more regularly.

Please extend my sincerest gratitude to the Committee members for their hard work and their valuable contributions to the Department and its mission.

Sincerely,

Dr. David T. Danielson
Assistant Secretary
Energy Efficiency and Renewable Energy

The Hydrogen and Fuel Cell Technical Advisory Committee
Washington, D.C.

May 28, 2015

The Honorable Dr. Ernest Moniz
Secretary of Energy
U.S. Department of Energy
1000 Independence Ave. SW
Washington, D.C. 20585

Dear Mr. Secretary:

Enclosed is the Hydrogen and Fuel Cell Technical Advisory Committee's (HTAC's) Annual Report on Hydrogen and Fuel Cell Commercialization and Technical Development. The Committee is once again pleased to report to you that the working relationships and the complementarity with the Fuel Cell Technologies Office are productive, fully functional and cooperative. The Office is well led and remains essential to addressing the Department's ongoing efforts on fuel cell durability, costs, advanced research and manufacturing, codes and standards and infrastructure. The Office has also monitored and advised the Committee with regard to the progress of fuel cell vehicle and stationary fuel cell advances in technology development and commercialization. Additionally the Office has provided invigorating leadership for H2USA, the public-private partnership focusing on fueling infrastructure for fuel cell electric vehicles.

As much as we celebrate and acknowledge progress, more hard work remains ahead for all of us and the Committee shares its current views with you to both seek your continuing support and assure you that our Members are fully committed to what is needed in the period ahead. Here are the highlights of what we bring to your attention and request your consideration as you consider the many priorities that compel you.

- The consumer incentive to purchase fuel cell vehicles has expired just as commercial vehicles are becoming available. We encourage you to support efforts to reinstate such incentives as complementary to state initiatives so that the vehicle launch is sustained. President Obama's 2016 Budget accommodates renewal of the incentive at a level of $10,000. Your assistance in making this proposal more visible and stimulating a debate would be a valuable first step in seeing its passage.
- The progress being made in California, including the creation of the re-fueling infrastructure, is an opportunity for you to bring these efforts to the attention of other states in the months and years ahead. California is committed to building an initial network of 100 hydrogen refueling stations in critical locations across the state, investing

$90 million to date, anticipating approximately 40 stations constructed by the end of this year. California is further supporting introduction of vehicles by providing rebates of $5000 to each FCEV purchased or leased for a period of at least three years.

- Your leadership of the Quadrennial Review and its focus on infrastructure is an excellent platform upon which to offer support to fuel cells for grid resiliency and storage.
- Considerable attention is being paid to hydrogen and fuel cell progress in Japan and Germany. Japan, in fact, has given hydrogen "the central role" in its low carbon energy future, and has committed more than $500 million this year for research and infrastructure deployment. The Committee remains convinced that the US has an opportunity to regain global competitiveness via increased coordination among the multiple stakeholders in the HFC community. Your active leadership together with the Department's convening authority could help re-invigorate the determination of US decision makers to keep moving forward by finding ways toward mutual support between government and private sector leaders.
- Budgetary support is the perennial item we bring to your attention. The Committee is grateful for the relatively stable level of funding that has been provided in recent years. Of course we would be neglecting our advisory purpose if we did not encourage you to consider a higher level of funding commensurate with global leadership vis a vis both Japan and Germany, considering the opportunity to move more rapidly now to commercialization and the need for infrastructure to support it.

The Committee also wishes to note the sustained support and engagement with key members of your leadership team, including Under Secretary for Science and Energy Franklin Orr, Assistant Secretary for EERE David Danielson, Director of the Office of Energy Policy and Systems Analysis Melanie Kenderdine and Deputy Assistant Secretary EERE Reuben Sarkar. We enjoyed the benefits of their advice and when possible their presence in our meetings during the past year. The Committee continues to assess all the efforts within the Department in order to advise you as best we can. The Committee also continues to utilize a pragmatic subcommittee structure that operates to focus attention on specific issues and opportunities, such as retail infrastructure, on behalf of the full Committee and the Program Office.

To place the 2014 Annual Letter in historic perspective and as prelude to next year's Annual Letter, the Committee notes that under EPAct 2005 the goals of the program were to A) enable a commitment by automakers no later than 2015 to offer safe, affordable and technically viable hydrogen vehicles in the mass consumer market; and B) to enable hydrogen production, delivery and acceptance for consumers of model year 2020 hydrogen fuel cell and hydrogen powered vehicles. Thus it was refreshing to witness the Department's video at a recent Committee meeting documenting your own "drive around town" earlier this year in the new Toyota *Mirai* and the obvious excitement you both displayed and generated among your passengers! This is clear progress against objectives over a sustained period. In addition, the EPAct has a section on grid infrastructure for 2015 that matches a commitment not later than 2015 that would lead to infrastructure in 2020, which fully complements the Department's Quadrennial Review activities of the past year. Thus the Committee appreciates and commends your personal leadership, clearly evidenced on multiple occasions, on behalf of the hydrogen and fuel cell future for the nation.

We look forward to continuing our service to you, your leadership team and the Program Office. It is a pleasure for us to serve the nation with our contributions to this important and innovative subset of the 21st Century US energy and environmental system. We welcome your feedback.

Via this letter I am also pleased to introduce you to my successor as Chairman of the HTAC, Frank Novachek, who has been unanimously selected by the Committee to serve in this role. He is the Manager of Planning and Technology Assessment at Xcel Energy. He is based in Colorado. Frank has been a member of the Committee for most of its history, served as Vice Chair over the past three years, and has been an active leader and participant in HTAC's subcommittee activities. My term as Chair expires on June 30, 2015. It has been a pleasure to support you and your leadership team at the Department of Energy and to serve my fellow Committee members as well. I also look forward to continuing to serve on the Committee.

Sincerely yours,

John Hofmeister
Chair
On behalf of the Hydrogen and Fuel Cell Technical Advisory Committee

2014 ANNUAL REPORT of The Hydrogen and Fuel Cell Technical Advisory Committee

Hydrogen and Fuel Cell Technical Development and Commercialization Activity

This Annual Report of the Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) highlights worldwide advances and challenges with regard to hydrogen and fuel cell commercialization, policy, regulations, standardization, financial climate, and research and development (R&D) during 2014.

Overall, the industry appears to be making headway. Even though it faces entrenched incumbents in power generation, combined heat and power, and forklift markets, the fuel cell industry has found competitive niches, albeit in most cases supported by incentives such as tax credits, renewable energy generation credits, direct payments, or concessionary regulations. The emergence of commercially available fuel cell electric vehicles (FCEVs) has captured the attention of governments and the general public, which bodes well for continued commercial expansion in 2015.

Summary

- A commercial fuel cell and hydrogen energy industry is emerging. Worldwide revenues may reach $2 billion[1] in 2015, dominated by the sale of large power systems. Markets are opening in Africa, South Asia, and South America.
- FCEVs are being sold and leased in Asia, Europe, and the United States (Fig. 1). California dedicated funds to an incentive program worth $5,000 per vehicle; Japan's federal government and the city of Tokyo announced a combined $27,000 per vehicle incentive.
- The number of residential fuel cell systems installed in homes in Japan exceeded 100,000 in 2014, aided by price reductions, continued government support, and consumer concern over energy reliability; new markets are opening in apartment buildings, where fuel cells are offered by builders as an appliance option.
- Total fuel cell power generation capacity in the United States was near 200 megawatts (MWs) by the end of 2014.
- After a difficult 2013, the market for fuel cell forklifts began to recover, led by an order of 1,783 units from Walmart.
- Several U.S. fuel cell companies improved their financial position, in some cases dramatically, through stock sales or private investment.
- Two well-established corporations—Doosan of South Korea and Hyster-Yale—entered the business; General Electric announced a commercialization initiative.

Governments, private companies, and investors made substantial commitments in 2014.

- Japan's new national energy policy gives hydrogen "the central role" in a new distributed energy system and sets ambitious targets for FCEVs and residential fuel cell sales. Japan's budget totals about $500 million for R&D, vehicle infrastructure, and deployment. Japan also set aside $350 million to showcase hydrogen and fuel cells at the 2020 Olympics.

Figure 1. On June 10, 2014, Hyundai leased the world's first mass-produced fuel cell vehicle in Huntington Beach, CA. *Image courtesy of Hyundai Motor America, Inc.*

- In Europe, the European Commission formalized a seven-year commitment for fuel cell and hydrogen research, development, and demonstration (RD&D) and increased its financial commitment to more than $800 million. Industry-led H2Mobility established a new corporation to build stations and sell hydrogen throughout Europe, with a budget of about $445 million, most of it from private funds.
- California, in 2013, pledged up to $20 million annually to finance 100 hydrogen stations; in 2014, Toyota and Honda supported the effort financially with a combined $22 million. Toyota and Air Liquide announced plans for 12 stations in New England.

- California also set aside up to $75 million for zero-emission trucks, buses, and goods movement.
- H2USA, a public-private effort to prepare the United States for FCEVs, contributed to extensive planning in the Northeast. Two national laboratories provide technical support through a partnership project called H2FIRST.[2]

Significant challenges remain for the industry.

- The U.S. federal tax credit for fuel cell power systems is scheduled to expire in 2016. The federal tax credit for FCEVs expired at year-end 2014.
- Two companies focusing on consumer electronics markets for fuel cells exited the business in 2014.
- Investor interest has been slow to return to the sector. After a roller coaster year, enterprise value for the four largest public North American fuel cell companies totaled $1.3 billion at year-end.
- Shipments of larger fuel cell power generation systems may have dipped; a few very large shipments were booked in 2013, and the market is still small.[3]
- FCEV production forecasts from industry for 2014-2016 are in the thousands of units; California projects a fleet of 6,650 vehicles by 2017 and 18,500 by 2020.
- Fuel cell system cost for light-duty vehicles, as estimated by the U.S. Department of Energy (DOE), appears to have hit a plateau.

HTAC Activities in 2014

In 2014, HTAC formed subcommittees to examine two critical issues: retail fueling infrastructure and advanced manufacturing techniques. These subcommittees will finish their work in 2015 and submit their conclusions and recommendations to the Secretary of Energy.

HTAC engaged several fuel cell manufacturers and users, as well as representatives of California and other states planning or implementing hydrogen infrastructure programs. Overall, significant progress is being made in a number of areas. Key issues to be overcome before FCEVs gain significant acceptance include vehicle cost; station cost; profitability; and technical issues such as fuel metering, fuel quality assurance, and station certification.

Commercialization Initiatives

Most segments of the hydrogen and fuel cell industry enjoyed significant commercial activity in 2014, a substantial share of which occurred outside the United States.

Fuel Cells for Stationary Applications: Fuel cells for distributed power continued to dominate the market in 2014, with 70% of total fuel cell units and more than 80% of megawatts shipped.[4]

- Japan's Ene-Farm residential fuel cell program passed several milestones. Installed units surpassed 100,000 in September, buoyed by price reductions and system improvements such as grid-independent capability. Ene-Farm units are now being sold by apartment building developers as an appliance, and more than 1,000 are on order. Government subsidies for the Ene-Farm program are declining and will end in 2016, although it is anticipated that some form of support will continue. The great majority of units are polymer electrolyte membrane (PEM); Japan Oil ended its residential solid oxide fuel cell (SOFC) program.
- In South Korea, POSCO Energy has placed orders for more than 270 MW of FuelCell Energy fuel cells. POSCO Energy, a division of South Korea's largest steel producer, operates the world's largest fuel cell installation and is building the capacity to produce 100 MW of fuel cells per year in South Korea by 2015.

Figure 2. The Dominion Bridgeport fuel cell park, consisting of five FuelCell Energy power plants, provides ultra-clean electricity around the clock. *Image courtesy of FuelCell Energy, Inc.*

- FuelCell Energy completed installation of a 14.9 MW fuel cell power park on only 1.5 acres of land in downtown Bridgeport, CT (Fig. 2). Dominion, the electric and gas utility, owns and operates the fuel cells.
- Bloom Energy reports it had about 130 MW of capacity installed in the United States in 2014, the majority in California, where Bloom has been very successful in gaining support from the state's Self Generation Incentive Program.
- A few demonstration power generation units are operating in Europe, along with more than 1,000 residential systems; another 1,000 are anticipated via a demonstration program called Ene.field.
- General Electric announced an internally funded spin-off, GE Fuel Cell Systems, to develop and commercialize a hybrid fuel cell turbine concept it claims will deliver up to 65% electrical efficiency. GE has been involved in fuel cell research for decades.

Fuel Cells for Transportation – Passenger Cars: Commercial sales and leases of FCEVs began in the U.S. and Japan in 2014.

- Hyundai recorded the first U.S. lease of its Tucson FCEV in June, to a family in Tustin, California.
- In December, Toyota offered its new FCEV, the Mirai, for sale in Japan, following a substantial publicity campaign. It plans to enter U.S. and European markets in fall 2015. Toyota reported greater than expected interest: orders quickly reached 1,500, mostly from corporate and government buyers.
- Honda, which had announced commercialization in 2015, announced a delay until 2016, citing financial pressure from safety recalls unrelated to its FCEVs.
- The Japanese government (¥2 million) and Tokyo government (¥1 million) announced purchase incentives totaling about $27,000 per vehicle.[5]
- Volkswagen (VW) showed three FCEVs at the Los Angeles Auto Show in November. VW also purchased Ballard's automotive fuel cell technology and agreed with SAIC in China to jointly develop fuel cells for automotive applications.
- Toyota made more than 5,000 hydrogen fuel cell patents, royalty free for five years, to spur development and innovation.

Fuel Cells for Transportation – Buses: The year featured planning and pledges for fuel cell buses, with procurements anticipated in 2015 or 2016.

- The U.S. Department of Transportation made funds available for low- or zero-emission buses, and in early 2015 it awarded $18.6 million[6] for 10 fuel cell buses—five each for transit agencies in California and Ohio.
- In Japan, Toyota's Hino Motors put a new fuel cell bus into service and hinted at commercialization in 2016.
- In Europe, five bus manufacturers signed a letter embracing fuel cell technology. Aberdeen took delivery of the first of 10 fuel cell buses and 8 buses are operating in London. North Rhine-Westphalia envisioned a joint procurement of 300 buses in 2016.
- Ballard ended its bus development relationship with Azure Hydrogen of China.

Fuel Cells for Transportation – Other Vehicles: Several demonstrations were announced in 2014.

- Alstom announced plans to build 40 fuel cell passenger rail cars.
- DOE is funding demonstrations in small numbers of terminal tractors, medium-duty delivery vans, a bucket truck, cargo tuggers (Fig. 3), and power units for refrigerated trailers. Budget for these market transformation programs was about $3 million in 2014.

Figure 3. FedEx, Plug Power, and partners are developing 15 fuel cell-powered tow tractors for use at Memphis International Airport. *Image courtesy of FedEx.*

Hydrogen Infrastructure: Although the worldwide hydrogen fueling infrastructure is still in its infancy, several hundred public stations are under construction or planned, with governments and private companies aiming for sufficient stations to support a rollout of vehicles between 2015 and 2017.

- In Japan, 45 stations are open or under construction, with a goal of 100 by the end of 2015. Government support increased in 2014 to about $88 million.
- The total number of hydrogen stations open in Europe by the end of 2015 could approach 80.
- Germany is targeting 50 stations by year-end 2015, with public financing of about $50 million secured.
- The H2 Mobility initiative in Europe focused on the deployment of stations in Germany, with a goal of 100 within four years and up to 400 by 2023, assuming sufficient vehicle sales. The large majority of the estimated $463 million cost will come from private sources.
- UK H2Mobility has a target of 65 stations; the United Kingdom (UK) government set aside about $8.7 million to upgrade 6–8 stations and share the cost of building 4–7 new ones.
- In Scandinavia, 16 stations are operating or under construction; at least 10 more are under review. Planning is also underway in France and Switzerland.
- In California, more than 50 stations were open or in progress at year-end, after the California Energy Commission awarded $46.6 million in May for 28 stations and a mobile refueler. A start-up, FirstElement Fuel, won financing for 19, with support from Toyota (at least $7.2 million) and Honda ($13.8 million).
- In November, Toyota and Air Liquide announced plans to build 12 stations in the Northeast, in states that have adopted California's Zero Emission Vehicle (ZEV) program.

- The ZEV program includes both obligations and incentives for automakers to sell zero-emission vehicles, including FCEVs. FCEV sales in California, or in any state that has adopted the ZEV regulations, earn credit toward obligations in all ZEV states, making FCEV sales highly valuable to automakers.

- As encouraging as they are, these efforts will provide only a skeletal infrastructure. There are more than 14,000 conventional gas stations in Germany, for example, and about 10,000 in California. As vehicle sales increase, infrastructure development will become a job for the private sector.

Fuel Cells for Materials Handling: The U.S. materials handling market recovered in 2014 after a poor 2013, led by an order from Walmart for 1,783 Plug Power units.

- According to DOE, about 7,500 fuel cell forklifts were in use or on order in the United States at the end of 2014.

- In 2014, Plug Power, the dominant supplier of fuel cells for forklifts, began to offer hydrogen fueling infrastructure. It markets this option—along with a service contract under the name GenKey®—as a turnkey product.

- A small number of forklift demonstrations are under way in Europe and Japan.

Fuel Cells for Backup Power Applications: Fuel cells are generally regarded as superior to diesel backup generators in many ways, including their greater reliability, lower emissions, better energy efficiency, and ready installation. Limitations on fuel cell backup power systems include siting restrictions, hydrogen fuel delivery, and cost.

- DOE estimates 4,000 fuel cell telecom backup power systems were in use in the United States in 2014.

- Fuel cells are also in use in smaller numbers at a wide variety of locations where losing power costs money or risks lives, including hospitals, grocery stores, data centers, schools, jails, and other locations.

- The market for fuel cell backup power is even more dynamic in the developing world, where grid power is sporadic or limited to certain hours each day. India, China, and Indonesia, among others, are using fuel cells in varying numbers. Companies pursuing those markets are optimistic that a fuel cell's ability to provide high quality continuous power for many hours per day gives them a competitive edge.

Hydrogen for Grid Support Applications: Electrolyzers are being evaluated to help smooth out generation from wind and solar systems and provide demand for renewable power when grid demand is low or constrained. The hydrogen thus produced can be used for a variety of purposes.

This type of grid support is increasingly necessary as the percentage of intermittent renewable generation increases. The approach is typically called "hydrogen energy storage" in the United States and "power to gas" or "P2G" in Europe.

- More than 30 P2G projects are under way in Europe, primarily in Germany, including at least two that feed hydrogen to the natural gas pipeline grid.

- In July, a $2 million hydrogen energy storage project was initiated for Ontario, Canada.

- Hydrogen energy storage is under study in California and New York, and at the federal level.

Other Applications: Fuel cells are making inroads in other markets, including military (e.g., unmanned vehicles, submarines and subsea weapons, and soldier and forward base power) and aerospace (e.g., auxiliary power for airliners and motive power for aircraft and drones).

Policy, Regulations, and Codes and Standards

Codes and Standards: Efforts to develop or revise safety and product standards made progress in 2014.

- In a major milestone, SAE International published two standards: Standard J2799 – 70 MPa Compressed Hydrogen Surface Vehicle Fueling Connection Device and Optional Vehicle to Station Communications, and Standard J2601 – Fueling Protocols for Light-Duty Gaseous Hydrogen Surface Vehicles.

- DOE released a smartphone app providing access to safety and planning information. DOE reported its safety education program has reached nearly 30,000 people.

- Japan made progress on a list of safety regulations to make them more suitable for hydrogen retail outlets.

- California adopted an expanded set of standards for hydrogen metering to enable retail fuel sales while encouraging development of higher accuracy meters.

- H2FIRST is examining station design as well as developing test devices to verify station fill protocol and hydrogen quality.

Policy: After years in the shadows, hydrogen and fuel cells regained some visibility in 2014 as contributors to sustainable energy systems, whether functioning as an energy carrier; balancing intermittent solar or wind generation; or providing low- or zero-emission power for homes, businesses, factories, or vehicles.

- Japan's 4th Strategic Energy Plan, adopted in April, gives hydrogen "the central role" in Japan's energy future. The "new energy model" emphasizes resilience, open access, and consumer choice.

- A companion hydrogen roadmap was published in June. Targets include 50%–70% of the new car fleet to be "new generation vehicles" by 2030, including FCEVs, as well as 1.4 million residential fuel cell units to be installed by 2020, and 5.3 million by 2030.

- Europe has set new CO_2 targets for new cars, to be phased in from 2015 to 2021, when the new car fleet average standard will be at 95 grams per kilometer, a 40% reduction from 2007 levels. The requirement gives super credits to manufacturers for extremely low-emission cars (50 grams per kilometer), providing incentives for battery electric and fuel cell electric vehicles.

- Germany adopted a new Electric Mobility Law in September that allows non-financial incentives for FCEVs and establishes labeling requirements.

- The UK government committed about $8.7 million (£5.5 million) to a $14.2 million (£9 million) program to bring the number of hydrogen stations to 15 by 2015. It made another $3.2 million (£2 million) available for vehicle purchases.

- California extended its Self-Generation Initiative Program, arguably the most important state-level incentive for fuel cells in the United States. Utilities will contribute $83 million per year through 2019, with 75% available for fuel cells and energy storage in 2015. There is a 20% bonus for California manufacture.

- In May, California joined many of its ZEV partners, including Connecticut, Maryland, Massachusetts, New York, Oregon, Rhode Island, and Vermont, in a Multi-State ZEV Action Plan to achieve 3.3 million ZEVs on the road by 2025.

Financial Climate

The capital markets were generally more receptive to hydrogen and fuel cell business models in 2014 than they have been in a number of years. Following a surge in public market valuations for several of the leading fuel cell companies in late 2013, a number of companies were able to raise substantial amounts of capital early in 2014.

- Plug Power completed a $22 million private financing and a $116 million underwritten public offering. M&T Bank agreed to finance Plug customers.

- FuelCell Energy (FCE) raised $29.4 million in an underwritten offering and received a $35 million equity infusion and $40 million line of credit from utility industry giant NRG. NRG also agreed to market FCE's fuel cells.

- Two early-stage UK fuel cell companies raised capital in the London markets. Intelligent Energy raised $68 million at an astonishing $1.1 billion valuation. Ceres raised $32.6 million on the AIM market.

- Private financing included $5.4 million to Heliocentris; an undisclosed amount to Sunfire of Germany, from Total; and a $40 million infusion to Altergy as a result of a legal settlement.

- Major utility Exelon announced it would provide equity financing for 21 MW of power projects utilizing Bloom Energy fuel cells.

Mergers and Acquisitions:

- Plug Power acquired Relion for $4 million in stock, materially less than the amount invested in Relion.

- South Korean company Doosan acquired Clear Edge Power for $32.4 million. ClearEdge had declared Chapter 11 bankruptcy only a year after it acquired the fuel cell assets of UTC Power (UTC) and only months after proclaiming a major expansion strategy.

- Hyster-Yale Materials Handling Inc. acquired Nuvera for an undisclosed price. Hyster-Yale expects to spend $40 million–$50 million to bring Nuvera fuel cell and hydrogen generation products to market.

- Ballard Power acquired the transportation fuel-cell-related intellectual property assets of UTC.[7]

- Hydrogen Future Corporation of Houston acquired Hydra Fuel Cell Corporation in a stock transaction.

In 2014, the sector also experienced the following setbacks, in addition to ClearEdge's bankruptcy:

- Danish company Haldor Topsoe closed its fuel cell division after investing almost $270 million. BIC, the French giant developing hydrogen storage technology for consumer products, exited the business.[8] Lilliputian Systems, a developer of SOFCs for portable power devices, liquidated its assets.

- Vision Industries of California filed Chapter 11 bankruptcy and will attempt to reorganize. Acta SpA, an Italian manufacturer of alkaline fuel cells and electrolyzers, also filed for bankruptcy protection.

Research and Development

Research and development can provide important support for commercialization activities. Some advances are being made toward key DOE targets, despite several years of declining budgets. Funding for vehicle-related R&D appears to have stabilized in the $100 million range. Funding for SECA, the solid oxide research program, was proposed at near zero again for fiscal year 2015; Congress approved $30 million (Fig. 4).

- With a $33 million program supporting 13 "medium-temperature" SOFC projects, the Advanced Research Projects Agency-Energy (ARPA-E) became a major contributor to fuel cell R&D.

Funding ($ in thousands)

Office of Energy Efficiency and Renewable Energy	FY 2013	FY 2014	FY 2015	FY 2016
Key Activity	**Approp.**	**Approp.**	**Approp.**	**Request**
Fuel Cell R&D	41,266	32,422	33,000	36,000
Hydrogen Fuel R&D[1]	31,682	34,467	35,200	41,200
Manufacturing R&D	1,899	2,879	3,000	4,000
Systems Analysis	2,838	3,000	3,000	3,000
Technology Validation	8,514	6,000	11,000	7,000
Safety, Codes and Standards	6,808	6,909	7,000	7,000
Market Transformation	2,838	2,841	3,000	3,000
NREL Site-Wide Facilities Support	0	1,000	1,800	1,800
SBIR/STTR	2,139	3,410	TBD	-----------
Total	**$97,984**	**$92,928**	**$97,000**	**$103,000**

Funding ($ in thousands)

Other DOE Offices	FY 2013	FY 2014	FY 2015
Basic Science[2]	26,000	~20,000	~20,000
Fossil Energy, SECA	24,000	30,000	30,000
ARPA-E[3]	2,000	~30,000	~33,000
Total	**$52,000**	**~$80 ,000**	**~$83,000**

1 Hydrogen Fuel R&D includes Hydrogen Production & Delivery R&D and Hydrogen Storage R&D
2 Estimated from FY14 appropriation
3 Estimated from FY14 appropriation. FY15 amount will depend on FOA selection.

Total FY15 Budget: ~$180M

Figure 4. Recent DOE funding for hydrogen and fuel cells R&D. *Source: U.S. Department of Energy, Fuel Cell Technologies Office.*

- University of Manchester (UK) researchers discovered that graphene material can filter elements at the atom scale and yet allow protons to pass through. This may serve as a technology for removing impurities from hydrogen fuel.

Significant progress in DOE-funded research in 2014 includes the following:

- Two national laboratories reported development of a new catalyst structure called a nanoframe that offers potential for more than 30x improvement in catalyst activity (Fig. 5). DOE estimates that catalyst costs represent nearly half of stack costs. DOE invested nearly $13 million in fuel-cell-catalyst-related R&D in FY 2014.
- Improvements allowed one membrane electrode assembly (MEA) to achieve DOE's 2014 target for specific power levels, though not the durability target. (Other MEAs had met the durability target but not the specific power target.)

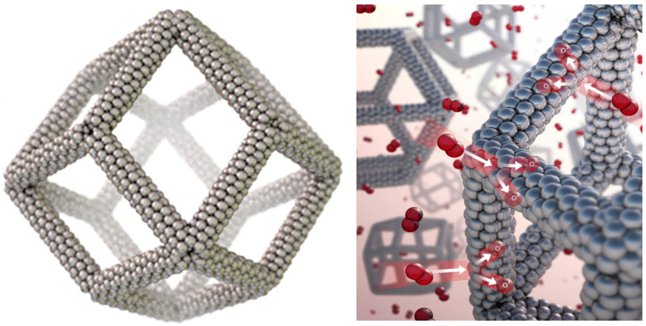


Figure 5. Platinum-nickel alloy nanoframe covered by a thin platinum skin, a new catalyst structure developed by researchers at Argonne National Laboratory and Lawrence Berkeley National Laboratory. *Image courtesy of Vojislav Stamenkovic, ANL, also printed in Science (343: 6177), 2014; pp. 1339–1343.*

- DOE reported a new fueling strategy to improve station capacities during peak hours. The technique reduces on-site compression requirements, yielding a 14% cost reduction for tube trailer hydrogen delivery.
- DOE also reported a continued improvement in carbon fiber tensile strength, which is important for high-pressure storage vessels.
- In hydrogen production, DOE reported improvements in electrolyzer drying techniques, in stability of photoelectrochemical devices, in reactor design for biological production, and in solar thermochemical materials and concepts.
- The number of fuel-cell-related patents remained strong in 2014, with 658 patents granted through three quarters, an increase of 36 year-over-year.[9] Toyota, Honda, and General Motors led the way.
- The cumulative number of patents resulting from DOE research exceeded 500.

Continuing Challenges: While deployment of fuel cells in various applications has been increasing, cost, technical, and marketplace challenges still hinder commercialization.

- Progress toward goals (Fig. 6) set by DOE has slowed over the past few years because of the difficulty in achieving the last increments and because funding has declined by more than half since 2007.
- The projected cost of vehicle fuel cells at 500,000 units per year has remained at about $55 per kW since 2010; catalysts and separator plates are 70% of stack costs. The long-term automotive fuel cell cost goal is $30 per kW, with $40 by 2020 an interim goal.

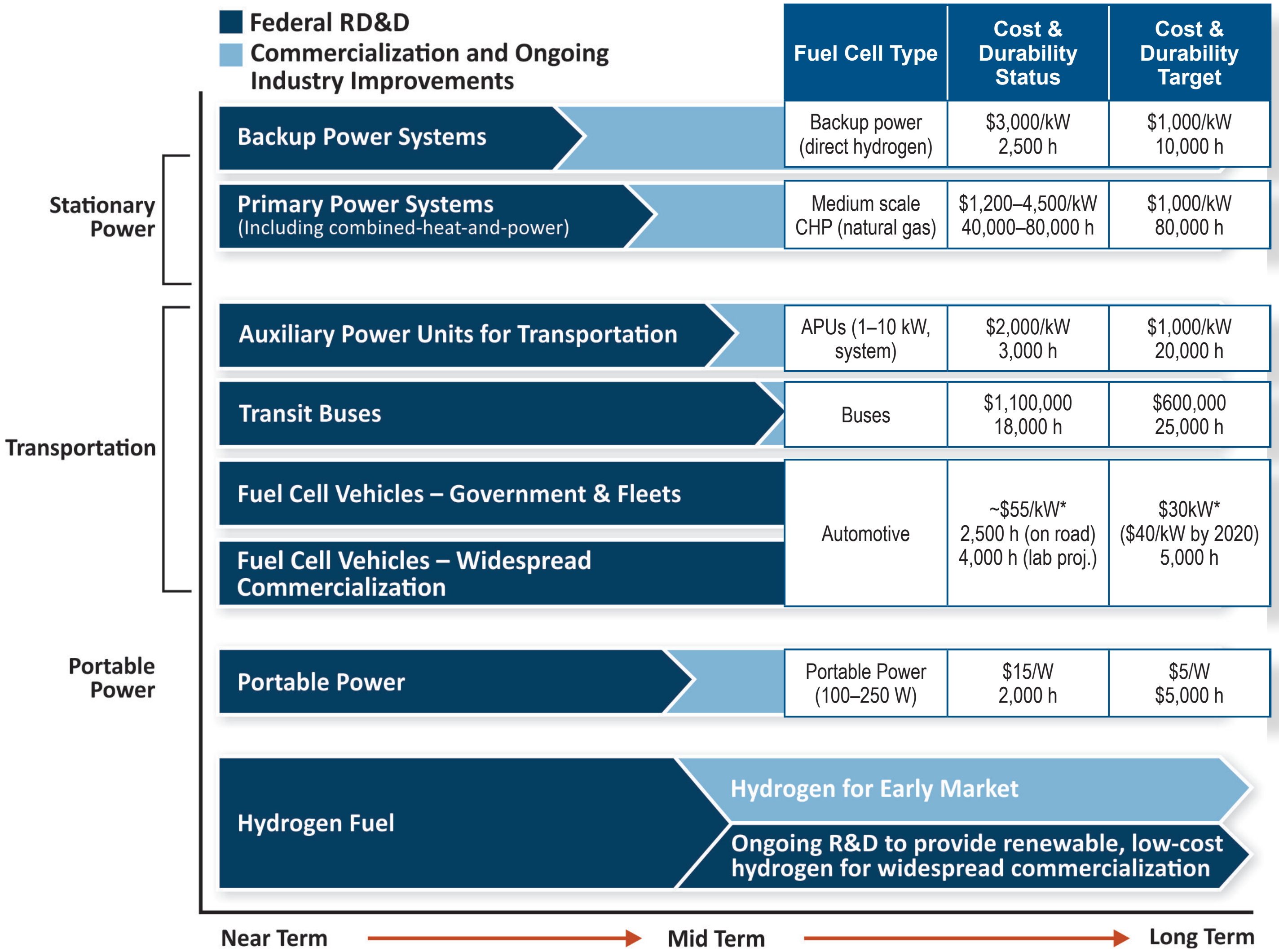


Figure 6. DOE targets and 2014 cost and durability status for fuel cells. *Source: U.S. Department of Energy, Fuel Cell Technologies Office.*

Reports

A number of reports on hydrogen and fuel cells were published in 2014.

- The California Air Resources Board (CARB) published its first *Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development*, as required by the California Legislature. CARB concluded 100 hydrogen stations will be needed to support the expected 2020 fleet.
- Japan's 4th Strategic Energy Plan, approved in April, gives hydrogen "the central role" in a new distributed energy system. Japan's METI published a *Strategic Road Map for Hydrogen and Fuel Cells* in June.
- DOE released the *2013 Fuel Cell Technologies Market Report* in the fall. It estimates fuel cell sales reached $1.3 billion and the number of systems shipped increased 26%.
- 4th Energy Wave's *Fuel Cell Annual Review 2013* estimates sales of $1.8 billion and notes a surge of interest in Africa.
- E4tech, a European consultancy, published its *Fuel Cell Industry Review 2014* in October, projecting another year-over-year increase in shipments.
- Breakthrough Technologies Institute published *The Business Case for Fuel Cells 2014*, latest in a series.
- The National Renewable Energy Laboratory updated its report on the performance of fuel cell buses, *Fuel Cell Buses in U.S. Transit Fleets: Current Status 2014*.

Conclusions

Three events have set the tone for fuel cell and hydrogen energy development over the next several years:

- Japan asserted world leadership in 2014 in the transition to hydrogen as a fuel and energy carrier. The Japanese government's choice of hydrogen in "the central role" in a new post-nuclear energy economy is by far the most ambitious country-level endorsement of hydrogen, made even more significant by Japan's status as a top world economy.

- Toyota, and to a lesser extent Honda, of Japan, asserted leadership in FCEVs, with Toyota beginning to market its new Mirai FCEV in December and both companies contributing to fueling infrastructure.
- Governments and private companies in Europe joined Japan and California in financing FCEV infrastructure development sufficient to support market launch in most of the developed world.

The burden now shifts to automakers to sell enough vehicles in a timely way to justify the investment.

The broad marketplace for fuel cell power generation and hydrogen energy is still in its infancy. It relies upon enlightened government activity for regulations, standardization efforts, R&D support, and marketplace incentives in most markets, and likely will for a long time. This is not exceptional. Incentives for solar and wind power systems are still needed despite their multi-gigawatt marketplace success. This need for support puts a burden on the policy community to balance the benefits of fuel cells and other advanced technologies against competing budgetary demands.

The opportunity is enormous. South Korea sees a potential for 2.8 million jobs worldwide over the next two decades. Japan sees its fuel cell market alone growing to $70 billion by 2050. DOE's analysis suggests a peak job potential of 560,000 U.S. jobs over the next two decades. The technology offers additional benefits in emissions, efficiency, fuel flexibility, greenhouse gas reduction, and grid resilience.

In the United States, 2015 will be a critical year.

The federal tax credit for FCEVs has expired, and the credit for power systems is scheduled to expire in 2016.

California's aggressive incentives have proved their value: the vast majority of FCEVs and power systems in the United States are located in the state. But California's market, big as it is, cannot drive commercialization of fuel cells by itself. Other states face decisions on whether and to what extent they wish to support fuel cells; a few have initiated support programs.

Beginning in 2015, states that have adopted California's ZEV program face a particular challenge and opportunity—without fueling infrastructure, there will be no FCEV sales in these states. The challenge will be to find and employ creative financing programs until vehicle sales are sufficient to support commercial fueling stations.

Significant technical challenges remain.

Fuel cells and hydrogen energy technologies have progressed to the point of commercialization in power generation, backup power, and materials handling markets. High system costs; customer unfamiliarity; and cost, production, and delivery challenges with hydrogen fuel remain market-limiting factors. In addition, fluctuating energy prices affect consumer choices and add market uncertainty.

Applying fuel cells and hydrogen technology to passenger vehicles is exceptionally challenging. Systems must be durable, lightweight, compact, cheap, and manufacturable in the millions of units. Hydrogen fueling stations must be customer friendly and reliable, as well as offer competitively priced fuel.

Toyota and Hyundai have demonstrated that fuel cells are developed to the point where functional, desirable vehicles can be manufactured. Figure 7 plots current status (in blue, expressed as a percentage) against 2020 targets set by a DOE/industry panel. It suggests much RD&D remains to achieve parity with incumbent technologies.

The benefits—zero emissions and ultimately zero petroleum consumption, with no sacrifice of vehicle performance or utility—suggest the importance of continuing a robust federal research program.

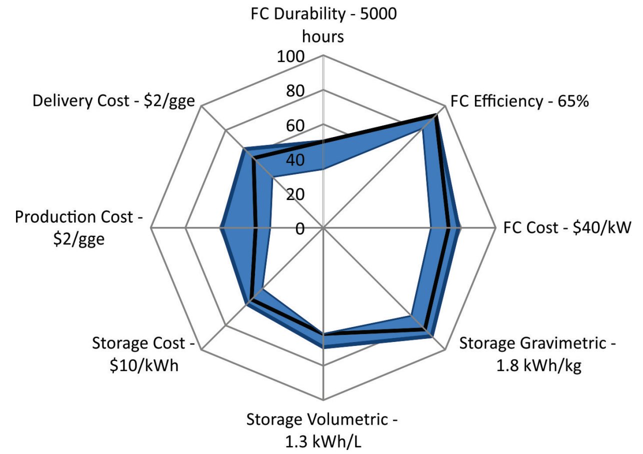


Figure 7. Hydrogen and transportation fuel cell status vs. 2020 DOE/industry targets.[10] *Source: DOE, Fuel Cell Technologies Office.*

(Endnotes)

1 *Fuel Cell Annual Review 2013*, 4th Energy Wave, 2014, p. 22. DOE's Annual Market review estimated revenues of $1.3 billion.

2 The formal name is "Hydrogen Fueling Infrastructure Research and Station Technology."

3 *Fuel Cell Industry Review 2014*, E4tech, 2014, p. 9 ff.

4 Ibid., p. 13.

5 Currency conversions are based on the Internal Revenue Service's 2014 annual average.

6 Early in 2015.

7 The intellectual property was sold to Volkswagen early in 2015.

8 Intelligent Energy bought the technology early in 2015.

9 Clean Energy Patent Growth Index, quarters 1–3, 2014.

10 Black line represents the state-of-the-art lab-scale technology status (projected to high volume) relative to the DOE's 2020 targets. Shaded area represents the range/error bars associated with the status projections at high volume.

The Hydrogen and Fuel Cell Technical Advisory Committee (HTAC) was established under Section 807 of the Energy Policy Act of 2005 to provide technical and programmatic advice to the Energy Secretary on DOE's hydrogen research, development, and demonstration efforts.

For more information see http://www.hydrogen.energy.gov/advisory_htac.html

The Secretary of Energy
Washington, DC 20585

September 21, 2015

Mr. John Hofmeister, Chair
Hydrogen and Fuel Cell Technical Advisory Committee
1302 Waugh Dr., #940
Houston, Texas 77019

Dear Mr. Hofmeister:

Thank you for your letter of May 28, 2015 accompanying the Hydrogen and Fuel Cell Technical Advisory Committee's (HTAC) seventh annual report on the state of hydrogen and fuel cell commercialization and technical development. The Department values the input of the Committee and sincerely appreciates its annual reports and recommendations.

Your report outlines many advances in hydrogen and fuel cells over the past year and summarizes key challenges. The Department recognizes that emerging technologies face a number of obstacles and continues to pursue a balanced strategy across basic and applied research and development. We are also addressing institutional challenges, such as codes and standards and infrastructure, particularly through our public-private partnership, H2USA.

We have noted your specific recommendation on increasing the visibility of President Obama's proposed tax incentive for alternative fueled vehicles as outlined in his FY 2016 budget request. To address your suggestions, the Department plans to develop a summary document to publicize the proposed tax credits which would include fuel cell electric vehicles.

We also noted the importance you place on a strong government budget and I am pleased to report that the 2016 budget request for the Fuel Cell Technologies Office was $103 million, roughly 10 percent higher than the 2015 request of about $93 million. In addition, we pay close attention to international activities and participate actively in the International Partnership for Hydrogen and Fuel Cells in the Economy, a government partnership among 17 countries and the European Commission that is focused entirely on accelerating progress in hydrogen and fuel cells. Our efforts provide valuable insight to enable domestic competitiveness.

As you know from your engagement with the Department, funding for the Office of Energy Efficiency and Renewable Energy has enabled more than 515 U.S. patents, 40 commercial technologies in the market related to hydrogen and fuel cells, and another 65 technologies we anticipate to be commercial in the next three-to-five years. Examples include catalysts, electrolyzers, fuel cell components, hydrogen storage tanks and other technologies to enable the successful commercialization of hydrogen and fuel cells. The Department is also engaging in a grid crosscut activity, and will be further exploring the potential role of hydrogen as energy storage and fuel.

With Mr. Frank Novachek of Xcel Energy as the incoming Chair, we look forward to further engaging on hydrogen energy storage for both grid resiliency and fuel applications. Finally, we'd like to request that the Committee provide feedback on the Department's Hydrogen and Fuel Cells Program Plan. HTAC provided valuable input to the 2011 version of the Plan, and the Department intends to update the document now that our Quadrennial Technology Review is complete. Your rigorous evaluation and input will be important as we update our plans, goals, and milestones.

Thank you for your engagement as Chair of HTAC over the past three years and close interaction with the Department at multiple levels, including Dr. Franklin Orr, Under Secretary for Science and Energy; Dr. David Danielson, Assistant Secretary for Energy Efficiency and Renewable Energy; Reuben Sarkar, Deputy Assistant Secretary for Sustainable Transportation, and Dr. Sunita Satyapal, Director of the Fuel Cell Technologies Office.

I look forward to the Committee's continued reports regarding the state of hydrogen and fuel cell technologies. Please extend my gratitude to the Committee for its insightful and valuable contributions to the Department.

Sincerely,

Ernest J. Moniz

cc: Frank Novachek