Hydrogen and fuel cell technology

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ABSTRACT

The Department of Energy's (DOE) hydrogen and fuel cell activities are presented, focusing on key targets and progress. Recent results on the cost, durability, and performance of fuel cells are discussed, along with the status of hydrogen-related technologies and cross-cutting activities. DOE has deployed fuel cells in key early markets, including backup power and forklifts. Recent analyses show that fuel cell electric vehicles (FCEVs) are among the most promising options to reduce greenhouse gas emissions and petroleum use. Preliminary analysis also indicates that the total cost of ownership of FCEVs will be comparable to other advanced vehicle and fuel options.

Keyword: -*: Hydrogen; Fuel cells; Total cost of ownership; -wheels studies Global view of fuel cells and clean energy technologies*

The Department of Energy's Office of Energy Efficiency and Renewable Energy invests in clean energy technologies to improve the economy, protect the environment, and reduce dependence on foreign oil. A single approach cannot solve the energy challenges facing the nation, so DOE supports research and development of a portfolio of clean energy technologies. Hydrogen and fuel cells are an integral part of the clean energy portfolio. Hydrogen can be produced from a number of diverse domestic resources, and fuel cells can generate electricity efficiently from a number of fuels, including biogas, natural gas, propane, methanol, diesel, and hydrogen.

Fuel cell markets

Various analyses project that the global market for fuel cells could mature in the next 10–20 years, with revenues in the billions of dollars per year for stationary, portable, and transportation applications. Increased market penetration could lead to almost 200,000 jobs in the US by 2020 and almost 700,000 jobs by 2035 [1]. In the near term, all applications of fuel cells need federal support. Applications of hydrogen and fuel cells in which a value proposition can be found, such as emergency backup power and forklifts, need less federal support and can be commercialized sooner. The technology for other applications, such as portable power, is not as mature and will need continued federal support. In the near term, all applications of hydrogen and fuel cells need federal research and development (R&D) support.

Interest in clean energy technologies, such as fuel cells, solar, wind, hybridelectric,biofuels,hydrogen, and geothermal, has been growing in recent years [2]. A measure of the level of interest of private industry is the number of patents issued for innovative concepts. The number of US patents for clean energy technologies in 2011 was at an all-time high of 2,331, i.e. 24% higher than in 2010. The most clean energy patents were for fuel cell technologies, with twice as many as the second-place holder, solar, which had just ~360 patents in 2010 and ~540 in 2011. In the marketplace, there has been a 36% increase in MW shipped globally, and a 50% increase in MW shipped in the US from 2009 to 2010.

1. The DOE Hydrogen and Fuel Cells Program

Hydrogen production and delivery The Fuel Cell Technologies Program is pursuing a number of pathways to generate hydrogen for fuel cells. These pathways include both distributed production in the near term and central production in the

1. Hydrogen storage

The Program is looking at several options to store adequate amounts of hydrogen onboard fuel cell vehicles. In the near term, compressed gas storage is the cheapest option; however, the cost of the tank still needs to be reduced. A cost analysis of Type IV tanks produced at high volume shows that more than 75% of the cost of the tank is due to the carbon fiber layers, and of that, 50% of the cost is from the precursor [3]. Efforts are being made to reduce the cost of the precursor and find ways to reduce the amount of carbon fiber needed without sacrificing safety. Currently there are hydrogen-powered fuel cell vehicles that have a range more than 250 miles; one vehicle from Honda traveled more than 430 miles on one fill. In the long term, hydrogen will be stored using materials such as chemical hydrides, metal hydrides, or sorbents. The Program has evaluated more than 400 material approaches in the laboratory. Fig. 2 shows the current status of gravimetric and volumetric capacity of 5.6 kg hydrogen storage systems including chemical hydrides, metal hydrides, sorbent and physical storage [4]. While some targets have been met, not all the storage targets have been met by a single technology simultaneously. long term.

100kW Pure hydrogen fuel cell cogeneration system CarNeu-100

The Program's hydrogen threshold cost is \$2–4/kg, to be competitive with advanced hybrid vehicles. Electrolysis, bio-derived liquids, and natural gas reforming can generate hydrogen in the near term. The projected high volume cost of hydrogen produced by these pathways is seen in Fig. 1. The cost includes compression, storage, and dispensing for distributed technologies, and the cost of delivery is included for central production. The ranges correspond to variability in the price of the feedstock. The pathways envisioned for central production include electrolysis and biomass gasification. The costs of producing hydrogen from those pathways need to come down significantly to reach the threshold cost and be competitive with the cost of other fuels. One of the biggest issues preventing the wide adoption of hydrogen-powered fuel cell vehicles is the lack of infrastructure. Several options for early hydrogen infrastructure have been proposed. In the first option, hydrogen is produced at a central location and then delivered to the point of use. In this case, hydrogen would be delivered by a tube trailer to a station at which a low volume of hydrogen, ~200–300 kg/day, is sold; would cost less than \$1 million; and provide hydrogen for around \$7/kg. In the long term, the volume would increase to 400–500 kg/day and the hydrogen would cost \$5/kg. The second main option would be distributed production, in which hydrogen is produced at the point of use and generated by steam methane reforming or electrolysis. Other options include regeneration, in which hydrogen is co-produced along with heat and power from natural gas or biogas feedstock.

Commercial hydrogen-electric energy storage system HyESS-C5

Projected capacities for complete H2 storage systems for chemical, metal hydride, sorbent, and physical storage technologies: (a) projected ranges of system gravimetric storage capacity, (b) projected ranges of system volumetric storage capacity. The red and purple lines correspond to 2010 and 2015 DOE targets, respectively. The height of the bars corresponds to the number of technologies examined in a given year

Project Value

With the delivery of the HyESS-C5 commercial hydrogen-electric energy storage system, HuaDe Hydrogen will start the continuous delivery of multiple HyESS series hydrogen and electricity energy storage systems. It is based on the design concept of high integration and high safety requirements of the HyESS series, combined with customers' different hydrogen production needs, fuel cell power generation needs and multiple hydrogen storage technologies. Route (including solid-state hydrogen storage, high-pressure hydrogen storage, etc.).

Fuel cells

One of the key issues preventing mass commercialization of fuel cells is the high cost of the system. The Program monitors the cost of 80 kW fuel cell systems for transportation applications to assess progress in its R&D efforts. The cost is projected to 500,000 units produced per year. In 2011, the projected cost of an 80 kW fuel cell system for light-duty vehicles was $49/kW [5], higher than the target of $30/kW required to be competitive with today’s vehicles. The projected cost is more than 30% lower than the estimate in 2008. Since the introduction of fuel cell vehicles will be at a volume lower than 500,000 units per year, the cost was projected at different manufacturing rates [5]. At 1000 vehicles per year, the system cost is around $219/kW, whereas at 30,000 vehicles per year, the cost is $82/kW.

Technology validation

The Technology Validation subprogram evaluates the performance and durability of hydrogen and fuel cell systems under real-world operating conditions. Past activities in the subprogram include driving fuel cell vehicles on the road and on dynamometers, dispensing hydrogen from refueling stations, and then assessing the status and progress of each technology. Since the Learning Demonstration effort began, the fuel cell electric vehicles were driven over 3.6 million miles and they operated ~2500 hours on average. Over 151,000 kg of hydrogen were produced or dispensed at the stations, although not all of the hydrogen was used in the Learning Demonstration vehicles. The evaluation effort has since expanded to other types of fuel cell vehicles, including fuel cell buses in cooperation with the Department of Transportation and forklifts located at a Department of Defense warehouse. The Technology Validation subprogram also monitors the performance and durability of stationary fuel cells.

The National Renewable Energy Laboratory (NREL) has evaluated data from the Technology Validation Program and from the fuel cells deployed using funding from the American Recovery and Reinvestment Act of 2009. NREL partners with end-users and fuel cell developers to create data sets and composite data products of the fuel cell systems operating under real-world conditions. NREL found that the fuel cell systems in backup power operated 1100 hours on average, with a projection to 2400 hours for a 10% degradation in voltage (a metric created to monitor durability at a set current density).

5kW natural gas integrated fuel cell cogeneration system (H2ES-5)

A very promising new activity in the Program is a combined heat, hydrogen, and power (CHHP) system, installed at the Orange County Sanitation District in Fountain Valley, California. The fuel cell system operates on hydrogen from anaerobic digestion of municipal wastewater, and is illustrated in Fig. 3. The unit generates heat, electricity, and hydrogen with 54% efficiency (hydrogen plus power) when operating in hydrogen co-production mode. With a compressor located onsite, the unit can provide 100 kg/day to refuel fuel cell vehicles. The public-access dispensing station was established by the project team of Air Products, Fuel Cell Energy, and the National Fuel Cell Research Center at UC Irvine.

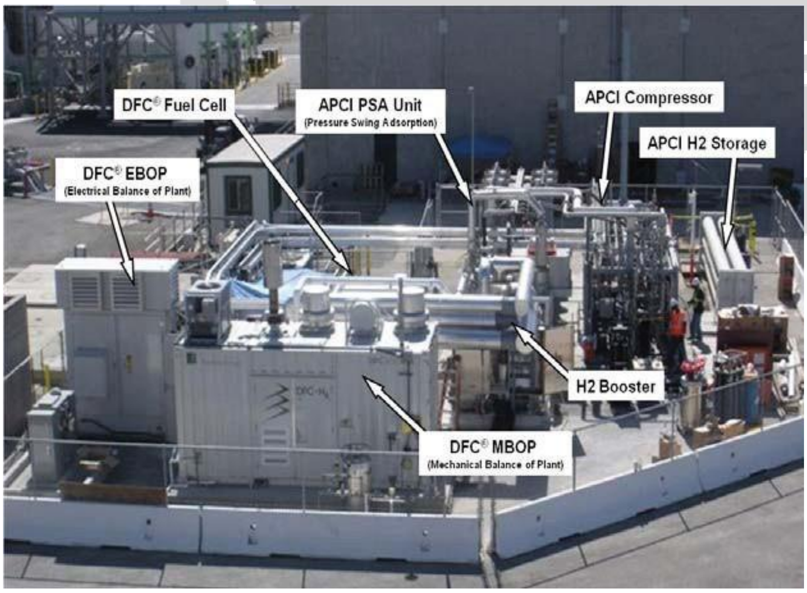

Fig. 3. Combined heat, hydrogen, and power (CHHP) system at the Orange County Sanitation District in Fountain Valley, California.

In 2009, the Fuel Cell Technologies Program awarded ~$42 million of funding from the 2009 American Recovery and Reinvestment Act (ARRA) to deploy fuel cell systems around the United States. The US Congress passed the ARRA to create new jobs in the US and save existing ones, spur economic activity, and invest in long-term economic growth. Including industry cost-share, the total funding for fuel cell deployment is $96 million. The fuel cells were deployed in the following early market applications: materials handling, backup power, residential and small commercial combined heat and power (CHP), portable power, and auxiliary power.

More than 1000 fuel cell systems are currently operational, and the majority are used for backup power at telecommunications sites and in forklifts for materials handling. Most of the fuel cell systems are deployed in California, Pennsylvania, and Texas. As of December 2011, the forklifts had been operated for almost 1 million hours. The ARRA projects were quite successful in the case of the forklifts, as the companies which used them now plan to deploy more than 3000 additional fuel cell-powered forklifts on their own, without federal funding. Compared to conventional forklifts, the maintenance cost of fuel cell-powered forklifts is lower, the labor cost to refuel the forklift is much lower, and the net present value of the total system cost is lower. In addition, the fuel cell-powered forklifts generate less greenhouse gases than conventional internal combustion engine (ICE) and battery electric forklifts.

Analyses

1. Well-to-wheel analyses

Figure 4 shows the greenhouse gases emitted in grams per mile for a variety of vehicles and fuels. The vehicles include conventional internal combustion engine (ICE) vehicles with today's technology, and also hybrid electric vehicles (HEVs) and plug-in HEVs, battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs) with propulsion technology assumed to be available in 2035. The fuels include gasoline, natural gas, hydrogen, and US Grid Mix electricity. Conventional IC engine vehicles fueled with ultra-low-carbon fuels from renewable resources and fuel cell vehicles running on hydrogen from biomass emit the least amount of greenhouse gases.

Additional analysis was carried out to determine the amount of petroleum energy consumed to propel a vehicle one mile, again for various types of vehicles and fuels. The results are shown in Figure 5. The most fossil fuel is used by conventional ICE vehicles fueled by gasoline. Battery electric vehicles, operating on electricity from ultra-low-carbon renewable resources and the grid mix in 2035, and fuel cell electric vehicles running on hydrogen from biomass or ultra-low-carbon renewable resources, consumed the least amount of petroleum energy. The Department of Energy supports research and development for all of these technologies.

1.1. Vehicle life cycle cost analysis

National Laboratory, NREL, and the DOE Biomass, Vehicles Technologies, and Fuel Cell Technologies Programs analyzed the life cycle cost of operating a vehicle they examined battery electric vehicles

Fuel cell electric vehicles, extended-range vehicles, combustion vehicles. The vehicles were fueled by hydrogen, gasoline, E85, and diesel. The cost is in dollars per mile for 2030 technology, except for a couple of ICE vehicles runningongasolineTh results are shown in *State activities for hydrogen and fuel cells* Not only do hydrogen and fuel cell activities occur at the national level, but many of the states have initiated their own programs, specific to their geographic regions. In California, more than 450 fuel cell electric vehicles have. Beeninoperation since 1999. Fuel cell buses operate on regular service routes near San Francisco and Palm Spring. California has many hydrogen stations, but most were built for research and development or as part of the Technology Validation effort. Many hydrogen refueling stations are behind fences or not available to the public. Looking to the future, the California Air Resources Board and the California Energy Commission have invested ~$34 million in hydrogen stations, with an million in industry cost-share. In 2010, the California Fuel Cell Partnership surveyed automakers, who predicted that sales of fuel cell electric vehicles in the state of California would dramatically increase after 2014

New York plans 100 hydrogen stations by 2020 to fuel 50,000 fuel cell six auto companies plan to invest nearly $3 billion in vehicles, while the state plans to provide $50 million for. New York State offers many tax credits, tax incentives and rebates for implementation of renewable resources and increased energy efficiency

The state of Hawaii has some of the highest electricity and gasoline prices in the nation. To address these challenges, Hawaii signed an agreement with General Motors, utilities such as The Gas Company, and the US Department of Energy and Department of Defense (DOD) to establish hydrogen as part of the solution to Hawaii's energy issues. In one of the DOE projects, electricity from geothermal and wind sources will be used to produce hydrogen, which will then be used to fuel buses on the Big Island of Hawaii. In cooperation with several DOD agencies and the car manufacturer GM, the US Army has just launched a pilot fleet of 16 vehicles powered by hydrogen fuel cells in Hawaii. Hawaii has also planned 20–25 hydrogen stations on Oahu to fuel the fuel cell vehicles

The FCT Program carries out communication and outreach activities to alert and inform its stakeholders on the continued progress in advancing hydrogen and fuel cell technologies. Webinars are held periodically on topics such as low- and zero-Pt catalysts; a database on hydrogen storage materials was launched; and blogs and news stories are released. A recent news story described the use of a fuel cell powered mobile light at the last NASA space shuttle launch; the mobile light has also been used at major Hollywood award shows such as the Grammys and Academy Awards [10]. In an announcement of fuel cell awards, Secretary of Energy Steven Chu noted that, 'These technologies are part of a broad portfolio that will create new American jobs, reduce carbon pollution, and increase our competitiveness in today's global clean energy economy'

The Fuel Cell Technologies Program also funds a number of documents and key reports. The report, *The Business Case for Fuel Cells*, profiles fuel cell customers and explains how the companies are saving time, money, and emissions by using fuel cells. The *State of the States: Fuel Cells in America* report highlights each state's activity and energy policies. The *2010 Fuel Cell Technologies Market Report* provides an overview of trends in the fuel cell industry and markets, including product shipments, market development, and corporate performance in 2010. A clear trend identified was continued growth in commercial deployments, largely in the materials handling, power, CHP, and backup and APU sectors. Other Program documents include the recently released Program Plan, as well as Proceedings from the Annual Merit Review and Peer Evaluation with a Peer Evaluation Report. The Annual Progress Report provides short technical reports from each of the projects funded by the Program, highlighting the accomplishments from each project and comparing the current status of the technology to DOE's technical and cost targets.

The FCT Program participates in international activities such as the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). The mission of IPHE is to organize and implement international research, development, demonstration, and commercial utilization activities related to hydrogen and fuel cell technologies. IPHE provides a forum for advancing policies and establishing harmonized regulations, codes, and standards. A recent product of IPHE is a cost comparison of fuel cell systems from different countries [12]. The Program also participates in the Hydrogen Implementing Agreement and Advanced Fuel Cells Implementing Agreement of the International Energy Agency. The purpose of the Implementing Agreements is to advance the state of understanding of hydrogen and advanced fuel cells through a coordinated program of research, technology development, and system analysis. These implementing

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Advanced fuel cells through a coordinated program of research, technology development, and system analysis. These implementing agreements support information exchange and task sharing with reports and databases as products. The FCT Program also has bilateral agreements with Brazil, Japan, Italy, and the European Commission.

1. Summary

The Fuel Cell Technologies Program continues to promote and strengthen its R&D activities. It is continuing to validate the technology in hydrogen stations, fuel cell vehicles, distributed generation, forklifts, and backup power. Analysis efforts explore not just upfront costs of hydrogen and fuel cell systems – although those are very important – but also life cycle costs, and the analyses are used to guide research, development and demonstration (RD&D) efforts. The Program continues to leverage other hydrogen and fuel cell activities in the US and globally to multiply and maximize the impact of our efforts.

The authors would like to thank the representatives from Argonne National Laboratory, National Renewable Energy Laboratory, and the DOE Biomass, Vehicle Technologies, and Fuel Cell Technologies Programs for providing results from their vehicle analyses.

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