RD&D Cooperation for the Development of Fuel Cell, Hybrid, and Electric Vehicles within the International Energy Agency

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Gabriela Telias
Austrian Agency for Alternative Propulsion Systems

Kristin Day
National Renewable Energy Laboratory

Philipp Dietrich
Paul Scherrer Institute

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RD&D Cooperation for the Development of Fuel Cell, Hybrid, and Electric Vehicles within the International Energy Agency

Gabriela Telias[1], Kristin Day[2], and Philipp Dietrich[3]

[1]Austrian Agency for Alternative Propulsion Systems (A3PS), Donau-City-Str. 1, Vienna A-1220, Austria
[2]National Renewable Energy Laboratory (NREL), 1617 Cole Blvd, Golden, CO 80401-3393, USA
[3]Paul Scherrer Institute (PSI), Villigen PSI CH-5232, Switzerland
E-mail: gabriela.telias@a3ps.at

Abstract—Annex XIII on "Fuel Cell Vehicles" of the Implementing Agreement Hybrid and Electric Vehicles of the International Energy Agency has been operating since 2006, complementing the ongoing activities on battery and hybrid electric vehicles within this group. This paper provides an overview of the Annex XIII final report for 2010, compiling an up-to-date, neutral, and comprehensive assessment of current trends in fuel cell vehicle technology and related policy. The technological description includes trends in system configuration as well as a review of the most relevant components including the fuel cell stack, batteries, and hydrogen storage. Results from fuel cell vehicle demonstration projects around the world and an overview of the successful implementation of fuel cells in specific transport niche markets will also be discussed. The final section of this report provides a detailed description of national research, development, and demonstration (RD&D) efforts worldwide.

Keywords—Fuel Cell Vehicles, International Energy Agency, Policy, Demonstration Projects, IA-HEV

1. Introduction

Concerns related to individual mobility, its dependence on fossil fuels, and its emission of significant levels of CO_2 worldwide is escalating. Government and industry are therefore forced to consider alternative and sustainable methods for transportation. Fuel cell vehicles (FCVs), for example, offer a unique advantage combining energy efficiency, emissions reduction, and reduced petroleum use and have thus become a research focus around the world.

The International Energy Agency (IEA) actively supports the development and market introduction of these and other new vehicle technologies. The Implementing Agreement on Hybrid and Electric Vehicle Technologies and Programs (IA-HEV) includes Annex XIII on "Fuel Cells Vehicles." Additional activities within the IA-HEV include, Annex XVII on "System Integration and Optimization of Components for Enhanced Overall Electric Vehicle Performance" which was created in June 2010. Annex XIII complements these and other activities related to electric and hybrid vehicles within the IA-HEV as well as the work completed under the Implementing Agreement on Advanced Fuel Cells (IA-AFC.)

The tasks foreseen for Annex XIII include an exchange of information between its member counties— Austria, Switzerland, and the United States—on national RD&D activities related to FCVs. This international cooperation assists in identifying global technological trends and development processes. The desired output is an impartial analysis of the state of FCV activities worldwide.

This paper summarizes the full report prepared by the members of Annex XIII. An up-to-date, neutral, and comprehensive overview on current trends in FCVs worldwide is provided as well as insight into current RD&D programs and strategies.

2. Fuel Cell Vehicle Technologies

The fuel cell technology on board vehicles is used for mainly two applications. This paper focuses on applications that provide propulsion to the vehicle. The fuel cell system functions as an energy converter, transforming a chemical energy carrier into electricity, which is then used in conjunction with an electric motor to propel the vehicle.

The second application of fuel cell technology on board a vehicle involves operation of its auxiliary units. This arrangement is applied predominantly in trucks, where power may be needed continuously during times when the truck is not moving, during sleep or recreation for instance.

For the first application, many of the open technical questions are in line with pure battery electric vehicles or with hybrid vehicles. For all the mentioned vehicle classes, electric motors/generators, power electronics, and wiring of power cables as well as electrical safety issues pose the same or similar questions. For example, questions regarding the electrical supply to the power steering system of the vehicle with 12-V DC or the production of a vacuum show joint challenges between FCVs and battery electric vehicles.

2.1 System Configurations

The fuel cell system can be viewed as a power converter unit that provides electricity and heat and therefore provides an analogous function in combination with an electric machine as the internal combustion engine in a conventional vehicle. The fuel cell system can be operated directly linked with an electric motor as a pure fuel cell powertrain. If this powertrain is combined with an energy storage system, the powertrain becomes a hybrid. In this case, the different functionalities of the power share used from the fuel cell or the energy storage system can be viewed as a conventional hybrid equipped with an internal combustion engine.

2.1.1 Pure Fuel Cell Vehicles

Pure FCVs require a fuel cell system that can cope with the dynamic power demands of the vehicle. The main requirements are:

- Maximum power: The power demand of the car is the same power as the maximum net power output of the fuel cell system. This power has to be provided not only as peak power but also for long-term operation at full speed or grading operation.
- Dynamic power adaptation: For fast acceleration, the production of power from the fuel cell system has to follow the demand instantaneously because there is no further energy storage system inside the vehicle. The reduction of power is in general no problem because the chemical reaction in the fuel cell is very fast.
- Starting time: The starting time of the fuel cell has to be in the same range as for internal combustion engine or battery electric vehicles.
- Cold temperature: The power output of a fuel cell system is temperature dependent. At lower temperatures the power output of the fuel cell may be reduced. Below 0°C, the start-up procedure has to cope with freezing water, which can increase start-up time. The starting time shall remain below half a minute.

2.1.2 Hybrid Fuel Cell Vehicles

The main structure of a hybrid fuel cell drivetrain is shown in Figure 1. The drivetrain consists of a fuel cell system, a storage device for electrical energy, power electronics, and the electric machine at a minimum.

This basic configuration can be adjusted depending on the power demands of the vehicle, the characteristics of each component, and the operating strategy.

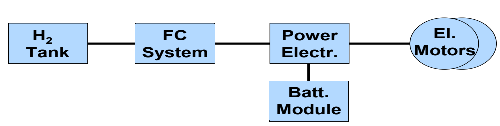

Figure 1: Scheme of the hybrid fuel cell powertrain

Typical demonstrated configurations are:

- Conventional hybrid: Most batteries are selected to store recuperation braking energy and to supply peaking power. As an alternative, a supercapacitor module has been introduced for short-term peak power demand.
- Plug-in hybrid: The vehicle can be operated with or without connection to the grid. For example, the battery can be charged from the fuel cell system, from the braking energy of the vehicle or it can be charged through connection to the grid. This presents the possibility of driving some moderate distance fueled by grid-supplied electricity.

2.1.3 Fuel Cells for Auxiliary Power

In general, the power demand for operation of the auxiliaries is significantly lower than that of the demands of vehicle propulsion. If hydrogen is stored on board, the fuel cell system is connected directly to the consumers via a DC link. If the vehicle is propelled by an internal combustion engine, the main fuel is diesel or gasoline, requiring a reformer to produce the hydrogen. In this case, the dynamics are defined by the reformer, and the electrical system needs an energy storage system to provide the power demands.

2.2 Relevant Components

FCVs require technologically advanced components not found in today's conventional vehicles to operate. The most apparent difference is the fuel cell, but many other components are needed for a complete and functional system.

The major components of a typical FCV include:

- Fuel cell system
- Power electronics
- Electric machines
- Energy storage system
- Hydrogen storage system.

The fuel cell system—consisting of the fuel cell stack, fuel processor, current inverters and conditioners, and a heat recovery system—uses hydrogen and oxygen to produce electricity.

For automotive use, polymer electrolyte fuel cells (PEFCs) are usually applied. Low-temperature fuel cells (<95°C) show overall good performance related to nominal power, cold temperature performance, and life. High-temperature PEFCs (160°C and 180°C) have advantages related to water management and CO-tolerance but face difficulties performing under low temperature conditions.

The fuel cell stacks, which consist of hundreds of cells with bipolar plates and membrane electrode assembly units, offer good potential for cost-effective production based on economy of scale. Metallic bipolar plates are the main option for large stacks; for smaller stacks, graphite-based bipolar plates are also used.

PEFCs can be operated at low pressure with the advantage of simpler auxiliaries, which results in less power demand for the air compression, but sophisticated humidity control is needed. With a high-pressure strategy, power density can be increased and water volume for humidity control is reduced by the addition of a compressor unit.

Power electronics, which include a motor controller, DC/DC converter, and inverter, process and control the electrical power flow between the fuel cell or battery and the electric machines. For instance, motor controllers regulate the power to the motor while DC/DC converters convert high DC voltage to low DC voltage. This voltage is then used to power the vehicle's auxiliary loads such as lighting, windshield wipers, and the radio. Lastly, inverters convert DC power from the fuel cell or battery to alternating current to power the electric machines.

The electric machines use the alternating current to provide traction to the wheels of the vehicle, thus enabling propulsion. Manufactures of current FCVs commonly use one of two electric machine technologies: permanent magnet (PM) or induction. Switched reluctance motors, although not commonly used as FCV drives today, are also being explored by researchers.

The majority of FCVs in operation today also take advantage of high power, high energy, and long cycle life energy storage devices to improve system performance. Slow dynamics as a result of temperature and fuel delivery to the fuel cell stack can result in significant voltage drops during rapid, high-load demands [1]. Energy storage devices have the ability to fill in these gaps and provide assistance to the fuel cell system during these events. Current energy storage technologies available for use in FCVs include lithium-ion, nickel-metal hydride, and lead-acid batteries, as well as ultracapacitors.

Lastly, an onboard hydrogen storage system is required. The development of a suitable onboard system to store hydrogen fuel remains one of the key challenges inhibiting the widespread commercialization of hydrogen FCVs. The issue lies in developing safe, reliable, and cost-effective systems within the mass and volume constraints of a vehicle. Currently, many prototype hydrogen-fueled vehicles use 35 or 70 MPa compressed hydrogen gas tanks for onboard storage. Research and development of additional technologies, including cryogenic liquid hydrogen tanks and materials-based storage, is also being conducted.

2.3 Fuel Cell Vehicle Operating Experience

A number of FCV demonstration projects have been and continue to be in operation around the world. These projects demonstrate FCV and hydrogen infrastructure performance in the real world. They offer the opportunity to gather valuable data—including fuel economy, driving range, refueling rates, driver feedback, and other factors—that can be used in working towards creative solutions to technical barriers facing hydrogen fuel cell technology in automobiles. In this section, select results and the status of notable passenger vehicle demonstration projects from around the world are highlighted.

2.3.1 North America

The Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, also known as the Learning Demonstration, is a U.S. Department of Energy project that began in 2004. Over 140 vehicles have been deployed, and 20 project refueling stations have been placed into use [1]. The fleet, which includes first- and second-generation vehicles, has surpassed 100,000 vehicle hours and traveled 2,300,000 miles, and over 115,000 kg of hydrogen have been produced or dispensed [2].

The Learning Demonstration fleet is made up of vehicles from four project teams, as indicated in Figure 2.

Figure 2: U.S. Learning Demonstration industry partners (Photo credit: Keith Wipke)

First-generation vehicles demonstrated fuel economies ranging from 42 to 57 miles/kg-H_2. The second-generation vehicles exhibited a slight improvement ranging from 43 to 58 miles/kg-H_2 [3]. Both first- and second-generation values are expressed using the pre-2008 U.S. Environmental Protection Agency (EPA) adjusted combined methodology.

In terms of driving range, a significant increase was observed from the first generation to the second generation vehicles. The EPA-adjusted combined driving range increased from 103 to 190 miles (first generation) to 196 to 254 miles (second generation). The improved range of the second-generation vehicles can be attributed to the change in onboard hydrogen storage systems. Most first-generation vehicles used 35-MPa compressed hydrogen tanks; whereas many second-generation vehicles employed 70-MPa compressed hydrogen tanks [2].

When considering commercialization of FCVs, it is also important to understand hydrogen refueling rates and how they compare to conventional vehicle refueling. Over 16,000 refueling events have been analyzed as part of the Learning Demonstration. On average, the time to refuel was 3.3 minutes with an average refueling rate of 0.78 kg/min [3].

The Learning Demonstration is scheduled to end in FY2011. Until then, vehicle and infrastructure data collection and analysis will continue. Lessons learned from the project will continue to be applied to technology evolution efforts and preparation for 2014 – 2015 market entry in the United States.

2.3.2 European Union

In November 2004, the Clean Energy Partnership (CEP) launched its demonstration project in Berlin, Germany. It is the largest project in Europe demonstrating the use of hydrogen-fueled vehicles in an everyday transportation environment [4].

At the completion of its first phase in June 2008, the demonstration project consisted of up to 24 hydrogen-fueled passenger vehicles. On average, 17 hydrogen-powered vehicles were in use: 15 using fuel cell technology and 2 using hydrogen-powered internal combustion engines. Three of the vehicles— one FCV and the two hydrogen-powered internal combustion engines—were driven by liquid hydrogen while the remaining 14 used compressed (35 MPa) gaseous hydrogen as their fuel [4].

The vehicles making up the CEP Demonstration Project fleet are shown in Figure 3.

Figure 3: CEP Demonstration Project fleet vehicles (Photo courtesy of the Clean Energy Partnership)

It is estimated that during the phase one test period 374,000 km (232,000 miles) were accumulated in Berlin city traffic without any noteworthy incidents [4]. The vehicle drivers, who were largely inexperienced in relation to hydrogen, were surveyed via questionnaire about their experience operating the hydrogen-powered vehicles. The feedback was extremely positive with the exception of criticism regarding vehicle range, which averaged 150 to 300 km (93 to 186 miles) [4].

The second phase of the CEP Demonstration Project is currently underway, and efforts to expand the fleet to 40 vehicles are in progress. Ten GM/Opel HydroGen4 vehicles, which use 70 MPa compressed gas hydrogen vessels for on-board hydrogen storage, for example, have already been added [4].

A third phase, scheduled to begin in 2011, will run through 2016. As with the U.S. Learning Demonstration, this final phase of the project will focus on drawing upon its learning's and preparing the market for the introduction of hydrogen in the transportation sector.

2.3.3 Japan

The Japan Hydrogen & Fuel Cell Demonstration Project (JHFC) is a national project consisting of a FCV demonstration study and a hydrogen infrastructure demonstration study.

The project is divided into two phases. JHFC Phase 1 ran from FY2002 through FY2005. The objective of this phase was to clarify the energy efficiency and the "well-to-wheel" efficiency of FCVs. The second phase began in FY2006 and is planned to run through FY2010. JHFC Phase 2 objectives are aimed at identifying issues found while operating FCVs and a hydrogen infrastructure under real-world conditions.

Eight domestic and foreign manufacturers provided six different FCVs, one fuel cell bus, and one hydrogen internal combustion engine vehicle to make up the JHFC fleet.

At the completion of JHFC Phase 1, the FCVs had accumulated 464,960 km (288,913 miles), and 23,213 kg of hydrogen had been dispensed. Phase 1 fuel consumption data were also collected and compared to fuel consumption values for internal combustion vehicles and hybrid electric vehicles. The data indicated that FCV fuel consumption was approximately 15 – 20% better than that of hybrid electric vehicles and 60 – 70% improved when comparing to internal combustion vehicles. The comparison was considered across a speed range of 20 – 80 km/h (12 – 50 mph) and on a gasoline equivalent basis [5].

The JHFC project is planned to end in 2010. The addition of a third phase, to run between 2011 and 2015, is under consideration [6]. In the meantime, the JHFC project will continue to focus on the objectives of Phase 2 and address challenges presented by 70-MPa infrastructure technologies, vehicle and station cost reduction, and the development of codes and standards.

3. International Policies and Funding Programs

This section identifies international trends regarding funding for RD&D activities related to fuel cell and hydrogen technologies for transport applications as well as the corresponding policies that provide the framework for these activities. The regions analyzed in this report include North America, the European Union, Japan, China, and South Korea. A short overview on the most relevant policies and strategies for the United States, the European Union, and Japan will be described next.

3.1 United States

In the case of the United States, clear performance and cost target criteria have been set for fuel cells and hydrogen technologies to promote the feasibility of their implementation in transport or auxiliary power applications.

The Fuel Cell Technologies Program is responsible for coordinating the research and development (R&D) activities for the Department of Energy's Hydrogen Program.

The program areas cover:

- Hydrogen production and delivery R&D
- Hydrogen storage R&D
- Fuel cell stack components R&D

- Technology validation for FCVs and hydrogen infrastructure
- Transportation fuel cell systems
- Distributed energy fuel cell systems for stationary applications
- Fuel processor R&D for stationary and transport applications
- Safety, codes & standards
- Education
- Systems analysis
- Market transformation
- Manufacturing R&D.

The key targets set by the Fuel Cell Technology Program (status 2010) for transport fuel cell systems are:

- Durability: 5,000 hours
- Costs: 30 USD/kW
- Efficiency: 60% at 25% power

3.2 European Union

The European Commission created the "Fuel Cells and Hydrogen Joint Technology Initiative" (FCH-JTI) in 2007; it is conceived as a public private partnership. The funding available for this initiative includes €470 M (~ 600 M USD) from the European Commission provided under the Seventh Research Framework Program (FP7); this sum is to be matched by the private sector. The goal of this initiative is to integrate all R&D activities and demonstration efforts under a common management to facilitate the process of setting budgets and timelines. Another goal of the FCH-JTI is to create links between demonstration projects and fundamental and applied research projects as a way to accelerate development.

The research agenda outlining the activities that will be supported by the FCH-JTI is set out in the Multi-Annual Implementation Plan (MAIP) of the FCH-JTI. The MAIP is translated into annual research priorities each year in an Annual Implementation Plan containing the specific topics for the calls for proposals. The MAIP is divided by application areas:

- Transport and refueling infrastructure
- Hydrogen production and distribution
- Stationary power generation and combined heat and power
- Early markets
- Cross-cutting issues.

The MAIP comprise the different phases of research technological development and demonstration including market support actions such as SME promotion and demand side measures.

The first call for proposals will be organized annually until 2013. Ongoing projects will be brought to conclusion by 2017.

3.3 Japan

The "Cool Earth – Innovative Energy Technology Program" for development of technologies in the field of energy based on the "Cool Earth 50" initiative was announced on May 2008. It includes a proposal for a long-term reduction of greenhouse gas emissions by 2050.

This program gives priority to 21 technologies based on their potential to reduce CO_2 emissions and to deliver substantial performance improvement, cost reduction, and increased diffusion as well as technologies where Japan could have the global lead.

FCVs are among these prioritized technologies together with plug-in hybrids and electric vehicles.

The technology development roadmap for FCVs foresees:

- Cost reduction of FCVs through technology development to 3 – 5 times those of internal combustion vehicles by 2010 and 1.2 times by 2020.
- Improvement of durability to 3,000 hours by 2010 and 5,000 hours by 2020 as well as cruising distance to 400 km by 2010 and 800 km by 2020.

4. Conclusions

In spite of the current, largely increased development efforts for battery electric vehicles and plug-in hybrid electric vehicles, most of the relevant manufacturers are continuing with their research activities on FCVs.

The list of shortcomings of FCVs has been reduced in recent years. Power density range and cold start capability cannot be seen as show-stoppers anymore. Durability is approaching the target range of 4,000 – 5,500 h of operation. Further improvements have to be achieved in terms of the investment costs of the powertrain and installation of an appropriate fuelling infrastructure. Regarding infrastructure, it might be possible in the future to learn from the establishment of the compressed natural gas infrastructure network for fueling stations. Another option that seems feasible, depending on the progress achieved on costs reduction, is to introduce the fuel cell system as a "range extender" in combination with a driving battery plugged or unplugged.

There will be competition on the technology side between the pure battery electric vehicle as the most efficient propulsion system (considering overall efficiency) and the FCV with the potential to have higher autonomy. But at the end, the outcome will be based in the combination of costs and convenience (autonomy, time of refill, available infrastructure), which will define the market segment and the share of these technologies in the markets.

The legislative framework conditions will help favor the most mature solutions or to support specific technology selection, leading to market distortion in the long run. In addition, the market development of resources and energy costs might be a driver to accelerate/decelerate the introduction of the new technologies.

Hybrid technology solutions might again be the bridge between mature and new technologies.

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7. Authors

Dr. Gabriela Telias
Austrian Agency for Alternative Propulsion Systems (A3PS)
Donau-City-Strasse 1
A-1220 Vienna, Austria
Tel: +43 (0)1 20501 68-105
Fax: +43 (0)1 20501 68-110
Email: gabriela.telias@a3ps.at
URL: www.a3ps.at

Ms. Kristin Day
National Renewable Energy Laboratory (NREL)
1617 Cole Boulevard m/s 1634
Golden, Colorado 80401-3393, USA
Tel: +1-303-275-4491
Fax: +1-303-275-3765
Email: kristin.day@nrel.gov
URL: www.nrel.gov/vehiclesandfuels/

Dr. Philipp Dietrich
Competence Center Energy and Mobility (CCEM) c/o Paul Scherrer Institute (PSI)
Tel: +41 (0)56 310 45 73
Fax: +41 (0)56 310 44 16
Email: philipp.dietrich@psi.ch
URL: www.ccem.ch

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