OECD/CSTP/TIP Energy Focus Group Report

Innovation in Fuel Cell Technologies in Japan: Development and Commercialization of Polymer Electrolyte Fuel Cells

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1. Introduction

In Japan, the government and many businesses have been pursuing the development of fuel cells since the early 1980s. The fuel cells currently being studied and developed in Japan and other nations can be largely divided into the following four types.

- Phosphoric acid fuel cell (PAFC)
- Solid oxide fuel cell (SOFC)
- Molten carbonate fuel cell (MCFC)
- Polymer electrolyte fuel cell (PEFC)

Of these, PEFCs are receiving the greatest amount of attention. The technical advantages of PEFCs over the other types include lower operating temperature and higher energy density. Consequently, it is technologically possible to miniaturize PEFCs and use them for not only industrial purposes, but also a broad range of applications that includes fuel cell cars and portable batteries.

Originally, PEFCs were developed for use in space, and were first employed in orbit aboard US Gemini V spacecraft in 1965. The Canadian firm Ballard Power Systems launched full-scale PEFC development in 1983 with funding from Canada’s Department of National Defense, and in 1987 demonstrated the potential for high power density by incorporating Dow membranes in their fuel cells. Around the same time, US Los Alamos National Laboratory showed that cells could be manufactured with reduced amounts of platinum. It was at this point that the global race by the private sector to develop PEFCs started. The low operating temperature made it possible to achieve compact, high density designs, and it became economically feasible to commercialize the cells. Because of these advances, PEFC developers started eyeing markets that could not be served by phosphoric acid fuel cells–namely, automobile, residential, and compact commercial applications. Under the “New Sunshine Plan,” the Japanese government initiated in 1993 a program for research and development on PEFCs for use in transportation and commercial applications.

The toughening of environmental regulations in North America pressed automobile manufacturers operating in that market to establish long-term environmental strategies, and thus they set about developing fuel-cell vehicles. Notably, the Japanese automobile industry began such development in 1992, and built test vehicles in the middle of the 1990s.

In 1998, the international competition to develop PEFCs was intensified when Daimler Chrysler, which partially capitalized Ballard with Ford Motor, announced that it would market in 2004 the world’s first practical fuel cell car. In Japan, industry-related organs of the government, perceiving the need to support automakers, electronics manufacturers, and other domestic industries, began actively pursuing policies aimed at supporting PEFC research and development and promoting the spread of PEFC use.

Focused on PEFCs, currently the subject of a worldwide development race, this report seeks to present an overview of the current PEFC development efforts of Japan’s government and industry, and in doing so, highlight features of the national innovation system that pertain to PEFCs.

2. Drivers of innovation

2.1 Background of energy technology innovation

As one of the few OECD members that possess almost no domestic primary energy resources, Japan has to rely almost completely on imports for its supply of fossil fuels–oil, coal, and natural gas. Moreover, the transportation of these imports entails enormous costs and instability of supply because Japan, unlike the nations of Europe, is not connected with its neighbors by land and is distant from the Middle East and other regions with abundant natural resources. Given these circumstances, the question of how to acquire a cheap and stable supply of energy is the most critical challenge that Japan faces in the formulation of its national energy strategies. Consequently, the fundamental approach of energy policy is to offset the lack of natural resources with technological competence–in other words, develop technology-intensive energy sources.

For a long time, nuclear power was the first choice as a form of technology-intensive energy. Combined cycle technologies, which increase power generation efficiency, photovoltaic (PV), and other renewable energy sources are among the various other technology-intensive energy sources that have been considered as candidates with much potential. In recent years, however, fuel cells have been rapidly gaining prominence as a promising technology that possesses many advantages when seen in the light of energy policy.

Along with energy policy, environmental policy has been growing increasingly important in OECD member nations in the past several years. In Japan, acid rain resulting from sulfur dioxide and nitrous oxide is not a serious problem. Similarly, water quality and air pollution–localized environmental problems–are not at a critical level. This is because measures dealing with these sorts of problems were implemented by the Japanese government throughout the 1960s and 1970s. In fact, it can be said that climatic change is the only environmental problem currently perceived as a national issue in Japan. Since the principal approach to mitigating climatic change is to curb the usage of fossil fuels, environmental policy is not in conflict with energy policy and thus helps drive energy technology development. Given the entrenched opposition to nuclear power, fuel cells are seen from the perspective of environmental policy as a more promising technology.

What sets fuel cell technology apart from other energy technologies is the broad involvement of many fields and industries in both the supply and demand of the technology. For example, power companies are the only direct users of nuclear energy, and it is very unlikely that any other direct users will appear in the future. In contrast, it is expected that there will be residential demand for fuel cell-based power generation, especially cogeneration. There is also enormous demand for fuel cell vehicles, more so than power generation, and demand for fuel cell-based portable batteries is growing gradually.

Seen from the supply side of technology, there are many industries that are involved in the technology–not only the energy, automobile, and electronics industries, but also such industries as material and chemical manufacturing. Hydrogen, the basic fuel of fuel cells, can be obtained by a variety of methods. Consequently, in order for fuel cells to be widely used in the future, it is necessary to develop an infrastructure for supporting fuel supply. It is likely that all sorts of industries will be involved in the development of this infrastructure–that is, the creation of the social systems needed for supplying hydrogen. In this respect, the impact of fuel cells on society as a whole will be of proportions not seen in other energy technologies.

2.2 Drivers of technological innovation

As illustrated above, Japan’s circumstances, the direction of energy and environmental policies, and the distinctive qualities of fuel cell technology have all combined to make the development of this technology a matter of great priority for both industry and the government. These two players, as will be described later, are sharing information and collaborating in development in an unprecedented manner. Under the government-industry partnership, the following factors are stimulating fuel cell development and driving innovation in this technology.

- Driver 1: Energy efficiency
- Driver 2: Reduced environmental impact
- Driver 3: Diversification of energy supply, and petroleum alternatives
- Driver 4: Distributed power generation
- Driver 5: Industrial competitiveness

These drivers are elucidated below.

Driver 1: Energy efficiency

Fuel cell technology directly converts chemical energy from the reaction of hydrogen and oxygen into electrical energy. Unlike conventional heat engines, electrical energy is obtained without combustion. Therefore, there is no upper limit on energy efficiency as set by the Carnot cycle’s theoretical thermal efficiency. Fuel cells thus offer much technological potential for the development of highly efficient power generation.

Take, for example, fuel cell use in automobiles. Compared with the energy efficiency of gasoline engines (around 15-20%), fuel cells, at their present level of development, offer greater energy efficiency of over 30% (this is affected by the type of fuel used in the cell). Moreover, this high degree of efficiency is attainable with small capacities at relatively low output levels, and theoretically it should be possible to achieve even greater efficiency in the future. (It is noted, however, that there is the possibility that the overall well-to-wheel efficiency balance may change depending on the fuels and reforming methods used. It should be noted that there is considerable room for argument when it comes to precise comparisons with hybrid, diesel, and other such vehicles.)

Next, let us consider stationary applications. Fuel cells generate electricity with an efficiency of approximately 35%, higher than the 25% efficiency of micro gas turbines, and attainable with small capacities and low outputs. This level may also fluctuate according to the type of fuel employed. However, greater efficiency is theoretically realizable. Since electrical power can be generated near the consumer area, exhaust heat could be used through cogeneration. Including this use of heat, overall efficiency in excess of 70% can be attained. Notably, the advent of the PEFC has boosted the potential for residential cogeneration.

As illustrated here, fuel cells offer immense potential in the improvement of energy efficiency. It is noted, however, that at present, these benefits are only prospects, and that their transformation to reality depends on the success of future R&D.

Driver 2: Reduced environmental impact

Because fuel cells directly produce electricity from hydrogen and oxygen, power generation does not entail the release of carbon dioxide or environmental pollutants. Producing hydrogen by reforming petroleum fuels inevitably emits carbon dioxide, but fuel cells' energy efficiency advantage over conventional heat engines means the amount of fuel needed decreases, and thus carbon dioxide emissions can be kept at a lower level. Furthermore, only a minute amount of NOx, SO2, PM, and other harmful substances are released when hydrogen is produced in this manner. If hydrogen is obtained from renewable energy sources, however, then fuel cell technology becomes a zero-emission energy source. Therefore, this technology can play an important role as a countermeasure for global warming and regional environmental problems. In addition, since fuel cells generate power through chemical reaction, little noise is produced. Whether used in automobiles or stationary applications, fuel cells can greatly help to reduce urban noise.

The properties noted above demonstrate that fuel cells can be fundamentally expected to reduce human impact on the environment. The degree of this benefit, however, may vary according to the overall scheme of systems used, including the fuel supply system, which is a critical issue in deciding the future of fuel cell-based systems.

Driver 3: Diversification of energy supply, and petroleum alternatives

Hydrogen, the fuel of fuel cells, can be converted from various fuels. Those primary fuels include natural gas, methanol, dimethyl ether derived from coal gas, gas-to-liquid (GTL) created from natural gas, and gasoline. Excluding gasoline, these fuels are alternative energy sources. In addition to fuel conversion, hydrogen can be produced through electrolysis using electricity generated by renewable energies, such as wind, solar, or geothermal power. Since renewable energies generally fluctuate in output and thus are unstable electrical power sources, energy supply systems with greater stability could be produced by combining these energies with fuels cells through hydrogen production.

As will be explained later, the Japanese government has a long history of R&D in hydrogen-based energy systems. Strategies for development of fuel cell technologies should take into account this track record.

Driver 4: Distributed power generation

Like micro gas turbines and diesel engines, stationary fuel cells can be counted on as a means of distributed power generation. Such distributed systems offer a number of advantages. First, power is generated near the consumer area, so the loss of energy in transmission (presently, 5% on average) is extremely small in comparison with the losses seen in large, centralized generation systems. Secondly, exhaust heat can be used through cogeneration. Thirdly, distributed systems can be used as backup power sources after a natural disaster or other catastrophe occurs. Moreover, fuel cells could be combined with PVs to produce small-scale residential power sources with improved stability.

Driver 5: Industrial competitiveness

A diverse range of industries are involved in fuel cell development, including the automobile, electronics, material, chemical, and energy industries. Enhancement of fuel cell technology would create jobs and new business opportunities in these industries and fortify their international competitiveness. The increased prosperity of these industries would, in turn, help to reinforce Japan's industrial might.

Over recent years, the automobile industry has been seeing a worldwide trend toward enactment of more stringent environmental standards. For Japanese automakers, fuel cell development is a critical challenge in their strategies for maintaining international competitiveness. In addition, considering that resource-scarce Japan almost completely depends on imports for its oil and natural gas needs, improvement of energy efficiency, diversification of energy sources, and movement away from petroleum dependence would lead to a radical strengthening of Japanese industry's global competitiveness.

3. Innovation system in the energy sector – knowledge creation, diffusion and exploitation

3.1 Actors

Of the various types of fuel cells, the potential for practical development of PEFCs has been rapidly growing in recent years. The government and many industries are the main actors driving this movement toward practical application of PEFCs.

Actor 1: Government

The government's efforts in making PEFCs a practical system have been led by primarily the Ministry of Economy, Trade and Industry (METI). Full-fledged involvement began with the "New Sunshine Plan" initiated in 1993. Aimed at comprehensively promoting technologies for renewables, energy conservation, and environmental protection, the plan is a governmental R&D project that combines the following three pre-existing programs:

- The "Sunshine Plan" for R&D in renewables (initiated in 1974)
- The "Moonlight Plan" for R&D in energy conservation technologies (initiated in 1978)
- Research projects for environmental technologies (initiated in 1989)

Fuel cell technologies were seen as important technologies in each of these three programs. In fact, research and development was started for SOFCs in 1974, and for MCFCs and PAFCs in 1981 in these programs. Under the New Sunshine Plan, the government launched in 1992 the project "R&D on High Efficiency Energy System Technologies for Transportation and Commercial Sectors," in which elemental technologies and systems for PEFCs have been studied and developed.

The core project of the New Sunshine Plan is the "International Clean Energy System Technology Utilizing Hydrogen Project," also known as the "World Energy Network Project" or "WE-NET." This project pursues R&D on technologies for hydrogen supply and demand systems for producing hydrogen with renewable energies and using it in a broad spectrum of fields. Under the Phase II program (FY 1999-2003) of this project, emphasis was placed on distributed hydrogen utilization technologies, and demonstration testing was conducted on hydrogen storage technologies and hydrogen supply stations. These hydrogen-related technologies are perceived as fulfilling a vital role in the creation of the fuel supply infrastructure for fuel cells.

Apart from the New Sunshine Plan, a government project funded by the revised budget for FY 1998 implemented the world's first operational test of an experimental natural gas-based residential cogeneration system in a house built for testing purposes.

The first full-scale efforts to commercialize PEFCs were initiated under a sub-project incorporated in the "Millennium Project" in FY 2000. Named for the new millennium, this project was established by the Obuchi Cabinet as a national R&D initiative founded on collaboration by the government, industry, and universities. The government invests research funds in the three focal areas of information technology, environment, and measures for dealing with the aging of the population. PEFCs are included in the project as a technology for supporting the prevention of global warming, and this technology is to be introduced for use in automobiles and residential applications. Specifically, the "Groundwork Project for Diffusion of Fuel Cells" was launched in FY 2000 to develop testing and evaluative methods for use in the formulation of safety and reliability standards for PEFCs.

Two other projects that have been running parallel with the Millennium Project since FY 2000 are the "Project for Development of Platform Technologies for Highly Efficient Fuel Cell Systems" for developing fuel cell test devices, and the "Project for Development of Technologies for the Commercialization of Highly Efficient Fuel Cell Systems" aimed at developing the industrial, cost reduction, and mass production technologies needed to commercialize fuel cells.

Predating these projects is the "Project for Development and Demonstration of Platform Technology for Commercialization of Fuel Cells" inaugurated under the secondary revised budget of FY 1999. This project was conducted to develop and demonstrate hydrogen fuel storage technology and fuel reforming technology.

Some ministries other than Ministry of Economy, Trade and Industry are also engaged in fuel cell-related R&D. Since FY 1999 the Ministry of Land, Infrastructure and Transport has been running the "Council for Appraising and Examining Fuel Cell Vehicle Technologies" in order to study issues related to the introduction fuel cell vehicles, including safety and environmental impact. Moreover, as part of the model program for environmentally friendly residential communities launched in FY 1998, the ministry has been providing financial assistance to residential communities that implement fuel cell-based cogeneration systems. And, since FY 1999, the ministry has been conducting investigative research on the implementation of home-purpose fuel cells.

A research institute operated by the Ministry of Agriculture, Forestry and Fisheries is currently researching the production of fuel cell fuels from biomass.

Actor 2: Industry

Numerous industries are involved in fuel cell technology, including the automobile, electronics, and materials industries, as well as such energy industries as petroleum, gas, liquefied petroleum (LP) gas, and electric power.

Automobile industry:

Since around 1996, Japan's automakers have been engaging in full-scale development of fuel cell vehicles (FCV). This movement was very likely motivated by American auto manufacturers' commitment of effort to FCV development in response to a series of FCV-related policies adopted by the American government in the 1990s, including the Energy Policy Act of 1992, the Spark M. Matsunaga Hydrogen Research, Development, and Demonstration Program Act of 1990, the Clinton Administration's advocacy of the Partnership for a New Generation of Vehicles in 1993, and the Hydrogen Future Act of 1996, which revised the Matsunaga Hydrogen Program. The industry is focusing its attention on PEFCs as the most suitable fuel cell type for use in FCVs.

Toyota, Honda, and Nissan announced in July 2002 that they had started limited sales of FCVs in line with their goal of developing practical FCVs around 2003 or 2004. A major development challenge that lies ahead for them is to find ways to bring down the cost of FCVs. With the enactment of zero-emission vehicle (ZEV) regulations in California, it has become important for Japanese automakers to come up with development strategies in tune with the American market. The three firms mentioned above are participating in the California Fuel Cell Partnership (CFCP). Following these companies on the development trail are such players as Mitsubishi, Mazda, Daihatsu, Suzuki, and Fuji Heavy Industries.

Because automobiles are an international commodity, the global community recognizes the need to create and refine international standards for the relatively nascent technology of fuel cells. Japanese automakers are seeking to have their opinions assimilated into the *de jure* standards to arise out of the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC), and at the same time are keeping an eye on emerging trends in the formation of *de facto* standards.

A variety of FCV types are possible, including pure hydrogen vehicles, methanol-reforming vehicles, and gasoline-reforming vehicles. The question of which to adopt depends on the nature of the fuel supply infrastructure to be developed, and the direction of Japan's overall energy policies. At present, Japanese automakers are pursuing their own individual paths in development, and have yet to announce any final decisions on the FCV type they will adopt.

Electronics industry:

Electronics manufacturers have heretofore been concentrating on PAFC development, which is now at a practical level for commercial and industrial applications. PEFCs, however, operate at lower temperatures and thus are promising for use in home, compact commercial, and mobile phone applications. Consequently, electronics manufacturers, like automakers, are committing themselves to PEFC development with an eye on opening up new markets for PEFCs. The main challenges they face in development include improvement of reforming technologies for such fuels as natural gas and LP gas, augmentation of power generation efficiency, and development of exhaust heat technologies.

Materials industry:

The materials industry plays a key role in supporting the elemental technology for PEFCs. Key material elements of PEFCs include polymer electrolyte membranes, electrode catalysts, and separators. Another important technology is the membrane electrode assembly (MEA), which merges membranes with electrode catalysts. Currently, there are a number of companies in Japan that possess advanced technology for manufacturing polymer electrolyte membranes. However, development of electrode catalysts, separators, and MEAs has not yet progressed to the stage of practical manufacturing. All these elemental technologies can be expected to deliver higher performance at lower costs.

Petroleum industry:

Petroleum companies are actively engaging in the development of technologies for reforming gasoline and kerosene, and for manufacturing GTL (Gas-to-Liquid).

Gas utilities:

Recognizing that the spread of fuel cell cogeneration systems will increase gas demand, gas utilities are placing high hopes on fuel cells. Up to now, this sector has focused on development and commercialization of PAFCs fueled with natural gas, but hereafter will shift emphasis to PEFC cogeneration systems that rely on reformed natural gas. The industry will also work on hydrogen manufacturing technologies for supporting fuel cell vehicles.

LP gas industry:

Currently some 300,000 LP gas vehicles, cars fueled with LP gas, are in operation in Japan, and approximately 1,900 LP gas stations exist nationwide. Seeking to capitalize on this existing network of stations, the LP gas industry holds great expectations for the commercialization of stationary fuel cells and fuel cell vehicles that both rely on reformed LP gas, and thus is vigorously pursuing the development of LP gas reforming technologies.

Electric utilities:

For many years, Japan's electric utilities have been regional monopolies, but they have been sustained by ten fully private firms. Many of these power companies possess in-house R&D units and actively engage in development. The industry has already accumulated more than a decade of experience in research on PAFCs, MCFCs, and SOFCs. Working with the aim of supporting power generation enterprises, the industry's developers previously exhibited keen interest in particularly MCFCs and SOFCs. In contrast, the industry did not place priority on PEFCs, whose potential lies in mainly distributed power generation applications.

In the late 1990s, however, power companies started having their subsidiaries pioneer markets for distributed power generation using kerosene and municipal gas. At the same time, they initiated research into the technical problems and future potentials of system interconnection in distributed power generation. As a result, they have started to assess the merits of PEFCs in terms of such qualities as energy efficiency, durability, maintainability, safety, and economics.

Venture companies:

Heretofore fuel cell development in Japan has been the work of large existing companies, with practically no parallels to the venture company-based development witnessed in such nations as the USA and Canada. In recent years, however, revisions to Japan's Commercial Law have made it easier to establish joint-stock companies, and the resolution of the bad debt problem that had saddled major city banks has loosened financing for smaller businesses. These and other climatic changes point to prospects for increased spinning off by large companies in the coming years.

3.2 Network of knowledge

The Fuel Cell Commercialization Strategy Study Group was launched in December 1999 as a private research group of the Director General of METI's Agency of Natural Resources and Energy. The purpose of this group is to discuss and systematize the challenges blocking the path to PEFC commercialization, and to formulate recommendations on policies for resolving those problems. This body has "private" status because it was established not by legislation, but at the discretion of the Director General. In this respect, their discussions and policy recommendations hold no legal force, but by direct reporting to the Director General the group nevertheless can potentially have strong influence on the agency's policymaking.

The makeup of the group, which comprises 28 members representing academia, industry, and public research institutes, is as follows.

- University professors: 9
- Automakers: 4
- Petroleum suppliers: 3
- Electric utilities: 3
- Electronics manufacturers: 3
- Gas utilities: 2
- Materials manufacturers: 1
- National research institutes: 1
- New Energy and Industrial Technology Development Organization (NEDO): 1
- Journalists: 1

The participants from industry all represent major domestic manufacturers and energy suppliers. NEDO, a satellite body of METI, is a quasi-public organization that controls the allocation of funding for R&D deemed critical to Japan's energy policy.

The group has, on nine occasions, invited domestic and foreign representatives of major companies, experts, and policymakers (domestically, METI; internationally, the US Department of Energy) to provide lectures and engage in discussion on PEFC technology. The content of those discussions was compiled into the "Report of the Fuel Cell Commercialization Strategy Study Group" released in January 2001. In August of the same year, the group expanded and complemented the technological strategy-related portions of that report by issuing a second report, "Polymer Electrolyte Fuel Cell and Hydrogen Energy Technology Development Strategy." With respect to the development of fuel cell technologies, the latter document provided recommendations on role sharing by government, industry, and academia, concrete technical targets, and means of achieving those objectives.

In addition, the group suggested that the drive toward the commercialization and diffusion of PEFCs needed a forum in which the relevant members of Japan's private sector could examine and discuss pertinent subjects. This recommendation led to the establishment of the Fuel Cell Commercialization Conference of Japan (FCCJ) in March 2001. Composed of 134 corporate and individual members, the FCCJ covers nearly all domestic companies associated with fuel cell technology. The consortium is chaired by the Chairman and CEO of the Toshiba Corporation (one of Japan's leading electronics manufacturers) with the assistance of four vice-chairs who are leaders from businesses in petroleum supply (Nippon Oil), gas (Tokyo Gas), automobile manufacturing (Toyota) and consumer electronics (Matsushita Electric Industrial).

The FCCJ's mission and activities have two focuses:

・With the aim of working toward the commercialization and spread of PEFCs and other fuel cells, the FCCJ provides relevant companies with a forum for discussing technologically strategic problems.
・The FCCJ offers policy recommendations to the relevant ministries and agencies.

In July 2001, the FCCJ submitted to the government a report that outlined the group's policy recommendations.

3.3 Information sharing between government, industry, and academia

Seen in the light of technological strategies, fuel cell technology is distinctive for the fact that its associated elemental and system technologies span a broad range, and the fact that end use also comprises an assorted array of applications, including power generation for industrial, commercial, and residential use, portable batteries, and automobiles. As a result, the challenges that must be overcome are likewise diverse, and thus all issues cannot be easily tackled by a single company or industry working on its own.

In order to successfully work toward fuel cell commercialization, all relevant industries and the government need to suitably divide their roles and engage in organic and systematic efforts in which the overall vision for R&D and market cultivation is shared by every player. In this respect, there is great significance in the two aforementioned reports of the Fuel Cell Commercialization Strategy Study Group, and in the existence of the FCCJ as a consortium of private sector organizations. Currently, through these undertakings the government, industry, and academia share understanding on the following roadmap and crucial technological development challenges for PEFC commercialization, and on the manner in which they, the actors, are to divide their roles.

<u>Roadmap</u>

Phase I: Platform development and demonstration of technology (now to 2005)

At present, practical FCVs and stationary fuel cells have been developed and put onto the market, albeit to a limited degree. The period from now to 2005 is slated as a transitional phase for fully and extensively commercializing these products. The following specific undertakings are required in this phase.

・Industry compiles data on safety, reliability, and other qualities of fuel cells in accordance with the latest trends in technology, and also establishes procedures for testing and evaluating those aspects.
・Based on the results of the above work, governmental organizations formulate the

various criteria and standards needed, and re-examine the existing comprehensive guidelines, particularly the regulations dealing with the safe handling of hydrogen and other fuels.

- Those involved in R&D seek to improve basic performance and reduce costs for the common, foundational aspects of elemental technology.
- Demonstrative testing and assessments are carried out to confirm feasibility and increase public acceptance.

Phase II: Market Penetration (2005 to 2010)

The years 2005 to 2010 are for establishing complete, operational FCVs and stationary fuel cell products, and for developing the markets for them. During this phase, the supporting social infrastructure, including fuel supply systems, need to be built up in stages. The market penetration target for 2010 is envisioned as approximately 50,000 FCVs and about 2.1 million kW in stationary fuel cells. To attain these objectives, the following concrete tasks need to be executed.

- The relevant industries pursue R&D aimed at further enhancing performance and bringing down costs, while the government reinforces research efforts in the common elemental technologies that support industry's R&D.
- With respect to FCVs, fuel supply systems start to be phased in, and public institutions/facilities and public transportation operators respond by leading the way in the conversion to fuel cell-based public vehicles, buses, etc.
- Public facilities and other centers also lead the way in the deployment of stationary fuel cells.

Phase III: Diffusion (2010 and later)

Full-scale diffusion of fuel cells is perceived as progressing in 2010 and thereafter. It is greatly expected that the market will autonomously grow as the fuel supply systems become more or less solidified and mass production drives down prices. Market penetration in 2020 is targeted at nearly 5 million FCVs and 10 million kW in stationary fuel cells.

<u>Crucial technological development challenges</u>

Through the Fuel Cell Commercialization Strategy Study Group's coordination, the government, industry, and academia commonly recognize the following four areas as the critical challenges in technological development.

(1) Common elemental technology for fuel cell stacks

A common challenge in both FCVs and stationary fuel cells is the endeavor to improve performance, lower costs, and reduce resource consumption for the primary basic components fuel cells, including membranes, electrodes, catalysts, and separators.

(2) Hydrogen storage technology

In the long run, hydrogen is the most promising fuel for FCVs. It is vital that technologies related to hydrogen use, particularly storage technology, be firmly developed.

(3) On-board reforming technologies for liquid hydrocarbon fuels

The extensive use of hydrogen requires building up of the hydrogen supply infrastructure, and thus necessitates the creation of strategies for making use of existing supply systems for the time being. Liquid hydrocarbon fuels can serve these needs, and the development of practical on-board reforming technologies for those fuels is expected to considerably advance the diffusion of FCVs.

(4) Technologies for manufacturing Gas-to-Liquid (GTL) as a promising liquid hydrocarbon fuel

A type of liquid hydrocarbon fuel, GTL is synthesized from natural gas and other gas fuels. Its advantage as an alternative fuel is substantial, and it shows promise as a clean fuel free of sulfur and chemical compounds.

<u>Role sharing between government, industry, and academia</u>

The first report issued by the Fuel Cell Commercialization Strategy Study Group indicated the importance of suitable role division by government, industry, and universities in the drive toward fuel cell commercialization and diffusion. The fundamental concept of this strategy is to have the government and universities handle the basic research and platform technologies, while industry works on the technologies for commercialization. Specifically, these functions are to be divided as follows.

・The role of industry

Technological development for fuel cell commercialization and technological development based on business strategies should fundamentally be supported by private sector research funding. Notably, development of primary automobile technologies–the overall system, fuel cell stacks, reformers, drive systems, and other technologies–is already, given the nature of those technologies and the industry, in a state of competition. This is a domain in which the government should not intervene.

In the other direction, industry can play a vital role in assisting the government's formulation of long-term policies by offering recommendations on new needs related to both technological development and the support necessary for such development.

・The role of academia

Through government-funded basic research, universities, the National Institute of Advanced Industrial Science and Technology (AIST), and other research institutes can help the cause by seeking out technology seeds, illuminating the basic principles and the degradation process of fuel cells, creating materials databases, and making other contributions. They can further play an active role by creating partnerships with businesses and performing research commissioned by the private sector.

・The role of government

The crucial function of the government is the planning and framing of the development of fuel cell technologies. Based on this function, the government should support the development of common platform technologies, high-risk basic technologies, and infrastructure building technologies by commissioning R&D to the private sector, providing aid to businesses, offering competitive funding to universities and public labs, and implementing other forms of support.

In its second report, "Polymer Electrolyte Fuel Cell and Hydrogen Energy Technology Development Strategy," the Fuel Cell Commercialization Strategy Study Group offers, for each of the four development challenges above, more detailed descriptions of the classes of technological elements, and the division of roles by the government, industry, and academia.

4. Public policy for innovation in PEFC technologies

4.1 Governmental support of R&D

Government investment in PEFC research and development can be generally divided into basic research and commercialization research. As noted in section 3.1, up to FY 1999 the government supported mainly basic research, but subsequently shifted focus to research for commercialization. Below are some of the major projects that the government has pursued.

Basic Research

Examples of government-sponsored basic research include the following two projects conducted under the “New Sunshine Plan.”

1. The Agency of Industrial Science and Technology[1] and NEDO

- “R&D on High Efficiency Energy System Technologies for Transportation and Commercial Sectors” (a New Sunshine Plan project)
  Term: FY 1992-2000
  Budget: US$440 million* (New Sunshine Plan total, FY2000)
  *This and subsequent figures are based on a rate of US$1 = 120 yen.
  Performed by: National research institutes and other organizations

2. METI (formerly, MITI) and NEDO

- “International Clean Energy System Technology Utilizing Hydrogen Project”; also known as the “World Energy Network Project” (WE-NET Project)
  Term: WE-NET Phase II (FY 1999-2003)
  Budget: US$14 million (WE-NET total, FY 2000), US$23 million (FY2001)
  Performed by: Engineering Advancement Association of Japan, and other organizations

The first project did not focus solely on PEFCs, but did put emphasis on them as fuel cells for commercial and transportation applications. The research was conducted by the Agency of Industrial Science and Technology’s research institutes. The latter project was implemented under Phase II of WE-NET to research PEFCs as one form of hydrogen utilization technology. The actual work was parceled out to numerous domestic businesses through the Engineering Advancement Association of Japan.

R&D for Commercialization

The following four projects by METI (formerly, MITI) and NEDO represent research focused on more specific commercialization of PEFCs.

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1 In the January 2001 reorganization of ministries and agencies, the Ministry of International, Trade and Industry (MITI) became the Ministry of Economy, Trade and Industry (METI). In conjunction with this, MITI’s Agency of Industrial Science and Technology (AIST) was likewise realigned in April 2001, changing to the National Institute of Advanced Industrial Science and Technology, of the “new AIST.”

1. Development and Demonstration of Platform Technology for Commercialization of Fuel Cells
   Term: FY 1999
   Budget: NA

2. Development of Technologies for the Commercialization of Highly Efficient Fuel Cell Systems
   Term: FY 2000-2001
   Budget: US$14 million (FY 2001)

3. Ground Work Project for Diffusion of Fuel Cells (part of the “Millennium Project,” a national S&T project)
   Term: FY 2000-2001
   Budget: US$11 million (FY 2000)
   Performed by: Japan Automobile Research Institute (JARI), Japan Gas Association (JGA), and other organizations

4. Research and Development of PEFC Technologies
   Term: FY 2002-2004 (scheduled)
   Budget: US$26 million (FY 2001)
   Performed by: Japan Automobile Research Institute (JARI), the Japan Gas Association (JGA), and other organizations

METI’s full-fledged involvement in PEFC technology started in FY 2000, but this was prefigured by project no. 1 above, which was conducted in the same year that the Fuel Cell Commercialization Strategy Study Group was launched (December 1999). In FY 2000 METI initiated a two-year in-house project (no. 2 above) that ran parallel with a different METI project (no. 3 above) conducted as part of the Millennium Project. In FY 2002, these two programs were merged into project no. 4 above, which continues today. This project’s work is performed by the Japan Automobile Research Institute (JARI), the Japan Gas Association (JGA), and many other domestic manufacturers and gas utilities.

The aforementioned Fuel Cell Commercialization Strategy Study Group’s second report, “Polymer Electrolyte Fuel Cell and Hydrogen Energy Technology Development Strategy” (August 2001), stresses the need for the government, industry, and academia to cooperate in demonstration test projects and foundational projects for developing performance measures and standards. The project carried out since FY 2002 can be considered to have profoundly incorporated the report's suggestion.

Another effort aimed at commercialization is the following Ministry of Land, Infrastructure and Transport (MLIT) project.

- Next Generation Low-emission Car Development and Promotion Project
  Term: FY 2002-2003
  Budget: US$13 million

4.2 Demonstration Program

Acting on the recommendations in the Fuel Cell Commercialization Strategy Study Group's second report, "Polymer Electrolyte Fuel Cell and Hydrogen Energy Technology Development Strategy" (August 2001), the Agency of Natural Resources and Energy (ANRE) has been running since FY 2002 a demonstration program for fuel cell-based systems, including fuel supply infrastructures.

- Fuel Cell Demonstration Test Program
  Term: FY 2002-2004 (scheduled)
  Budget: US$21 million in FY 2002
  The program comprises two projects:
  - Project on fuel cell vehicles (FCVs) and hydrogen supply stations
  - Project on stationary fuel cells and cogeneration systems

  Performed by:
  - FCVs and hydrogen: Japan Electric Vehicle Association (JEVA) and Engineering Advancement Association of Japan (ENAA)
  - Cogeneration: New Energy Foundation (NEF)

This program collects, analyzes, and assesses demonstrative data on such items as environmental impact, fuel efficiency, total energy efficiency, and fuel supply infrastructure cost assessment. Broadly speaking, it is divided into two projects:

- A vehicle-purpose fuel cell project, which covers FCV road performance and hydrogen supply station operation
- A stationary fuel cell project, which covers stationary fuel cell-based cogeneration systems

In the vehicle-purpose fuel cell project, researchers are conducting public road tests of FCVs and operational tests of hydrogen supply stations. The public roads used include city streets, expressways, and mountain roads so that the FCVs can be tested under diverse traveling conditions. With respect to hydrogen supply infrastructure, researchers are testing various forms of fuel supply, including hydrogen, reforming from methanol, reforming from naphtha, electrolysis, and reforming from natural gas, and they are also testing modes of hydrogen storage, such as pressurized storage and liquefied storage.

The FCV road testing is being conducted under the leadership of the Japan Electric Vehicle Association (JEVA), with participation by General Motors, Daimler-Chrysler, Toyota, Nissan, Honda, and the Japan Automobile Research Institute (JARI), while the hydrogen supply infrastructure testing is being led by the Engineering Advancement Association of Japan (ENAA), with participation by Cosmo Oil, Nippon Oil, Tokyo Gas, Nippon Sanso, Air Liquide Japan, Iwatani International, Showa Shell Sekiyu, and Nippon Steel.

The stationary fuel cell project seeks to experiment with a variety of heat and electricity utilization patterns by testing both residential and commercial cogeneration in not only residential communities, but also industrial districts, coastal zones, cold-climate areas, and various other areas. In addition to operational testing, the project is also examining the impact posed to operation by power system interconnections. With New Energy Foundation (NEF) at the helm, this project has brought together such participants as Ebara, Nippon Oil, Sekisui Chemical, the Central Research Institute of the Electric Power Industry, Tokyo Electric Power, the Japan Gas Association, Sanyo Electric, Toshiba, Toyota, and Matsushita Electric Industrial.

5. Innovation performance and its assessment

Since fuel cell development is still an ongoing process, it is difficult at present to assess the performance of the innovation system that supports this technology. Here follows an examination of the current state of development in fuel cell technology, contrasting PEFCs with others types of fuel cells (PAFCs, SOFCs, and MCFCs).

As illustrated in the preceding sections, Japan’s latest efforts in PEFC development are highly distinctive in the fact that they are being implemented through close collaboration between industry and the government, as led by the Fuel Cell

Commercialization Strategy Study Group. This endeavor represents a new mode of cooperation that has not been seen in the R&D on other types of fuel cells, and that has rarely occurred in other areas of technology. In many of Japan's large-scale national R&D projects up to now, including those related to fuel cells, strategy has been formulated by the government (METI in most cases) and its national research institutes, overall research has been handled by NEDO and other governmental satellite organizations, and individual research tasks have been allocated to private companies. National R&D projects for fuel cells other than PEFCs are typical examples of this model.

The government's involvement in fuel cell development started with the Moonlight Plan (1981), which the former MITI's AIST launched in response to public recognition of the need for alternative energy sources and energy conservation in the wake of the two "oil shocks" that rocked Japan. Part of this plan called for the cultivation of domestic technology in PAFCs, an area that the US was leading at that time. Later, PAFC development was continued under the New Sunshine Plan, and was bought to a close in 1997 after the government decided that the commercial stage had been attained.

Unfortunately, it cannot be said that many noteworthy achievements arose from the government's involvement as a leader in these R&D projects. To date, some 200 PAFCs have been actually put to use, including those used for experimentation. However, as of late March 2001, only about 70 were in actual operation, and although currently several new units are put into use every year, they all depend on government subsidies, and consequently PAFC technology cannot be considered fully ready to stand on its own in the marketplace. Furthermore, at the outset of development, PAFCs were perceived as a first-rate, environmentally friendly technology for electric power generation, but judging by the current situation, they are not adequately meeting those expectations. Compared with existing power sources, PAFCs do not demonstrate significantly higher performance in power generation efficiency, and their cost still remains prohibitive. While PAFCs have the potential to generate electricity on a scale of 50 to 1,000 kW, the inherent properties of this technology limit it to service in commercial or industrial stationary power generation–a small niche market acutely sensitive to cost. Moreover, gas engines and other rival technologies in this market perform at levels far beyond what was imagined possible by the original planners of the PAFC project. Consequently, PAFCs are unable to attain the mass production-generated cost reductions forecast at the start of the project. While PAFC development did achieve its technical objectives, it has failed in terms of market diffusion and penetration.

A factor behind this failure is that, at the development planning stage, there was not enough analysis of the size and nature of the target market based on the fundamental properties of the technology, such as power generation efficiency and capacity. As a result, it is likely that the goals of development (performance, cost, timing of market entry, etc.) and the systems of development were inappropriately defined in some cases, and that the project implementers were unable to make course corrections to these goals and systems as the project progressed and the external environment changed.

Apart from PAFCs, development was started on SOFCs in 1974 under the Sunshine Plan, and on MCFCs in 1981 under the Moonlight Plan. Later, both of these projects were continued under the New Sunshine Plan, and today they are still underway. A solid assessment of their achievements cannot be made at this point, but it does seem that inordinate amounts of time and funding have been consumed by them.

The PEFC development effort has, in a sense, learned many things from the mistakes (or inadequacies) of the above projects for other types of fuel cells. Against that backdrop, the government, industry, and academia commonly recognize PEFC technology as being situated in the following environment.

1. External factors: Global competition in technological development has acutely intensified in recent years as energy and environmental problems received more attention.
2. Technical attributes: A broad range of industries are stakeholders, including the automobile, electronics, materials, intermediates/parts, chemical, petroleum, gas, electric power, and plant industries.
3. Market attributes: It is necessary to develop not only the fuel cells themselves, but also the fuel supply systems that support them.
4. Regulatory factors: Since this is a new area of technology, it is necessary to establish regulations and standardize the technology.

Given this situation, there is concern that timely commercialization and diffusion cannot be delivered by the traditional method of R&D–the bottom-up approach that linearly progresses through the stages of basic research, applied research, and practical research. There needs to be a new innovation system that can respond with flexibility and mobility to changes in both needs and the external environment. The new model for innovation–in which the private study groups of director generals at ministries and agencies promote information sharing by the government, industry, and academia, and make recommendations, based on which the government creates research projects while industry establishes forums for exchange between businesses–is greatly expected to successfully answer the demands not satisfied by the traditional approach.

6. Conclusions and issues for improving the innovation system

Fuel cells are a highly promising option for Japan’s energy and environmental policies, which seek to achieve greater diversity and flexibility in energy sources while also addressing the problem of global warming. Compared with other types of fuel cells, PEFCs operate at lower temperatures and technically can be engineered in compact designs. Consequently, they can be employed in an extensive range of applications, being suitable for residential and compact commercial power generation, FCVs, portable batteries, and other such uses. They offer technological benefits that greatly outclass other fuel cells in terms of higher energy efficiency, reduced environmental impact, and use as a petroleum alternative and as an element for distributed power generation. Pressed by greater environmental regulation around the globe since the mid-1990s, automakers have commenced full-scale development of PEFCs, and FCVs are now the subject of a worldwide race in technological development.

PEFCs have a bearing on a diverse array of fields in terms of not only demand, but also supply. The primary internal elements of fuel cells cannot exist without the materials and chemical industries. In addition, both stationary fuel cells and FCVs will not see widespread use without the social infrastructure for supplying the fuel they need. For the time being, this need will likely be filled through the use of existing gasoline stations, municipal gas supply systems, and LP gas supply systems. This will also require technologies for manufacturing liquid hydrocarbon fuels, such as Gas-to-Liquid (GTL) and other promising alternatives to petroleum, and technologies for on-board reforming. Looking to the future, it will be necessary to create the hydrogen-based fuel supply systems that will be used once all fuel cell applications are switched to hydrogen from all other fuels. At that time, the most important platform technology will likely be hydrogen storage technology. The formation of these social infrastructures will require a more comprehensive industrial network that goes beyond the conventional boundaries of industry.

Based on the above perception, the development of technology aimed at commercializing PEFCs is a matter of high priority for both industry and the government. In view of the broad permeation of the technology on both the supply side and the demand side, the government, industry, and academia are now pursuing development by sharing information and collaborating in a manner unprecedented by any other national technological development project. One manifestation of this collaboration is the Fuel Cell Commercialization Strategy Study Group that was launched in December 1999 as a private research group of the Director General of METI's Agency of Natural Resources and Energy, and its offspring, the Fuel Cell Commercialization Conference of Japan (FCCJ), a consortium of about 130 businesses that was established in March 2001. Since the former has the status of a private study group under the Director General, its decisions and reports are not legally binding, but they do have considerable impact on subsequent R&D programs of METI. Aimed at supporting the commercialization and diffusion of the various types of fuel cells, the FCCJ provides a forum in which relevant companies can discuss technologically strategic issues and make recommendations to the government concerning domestic and international standardization of technologies, and regarding laws and regulations. Because of these efforts, the relevant industries, the government, and academia share the same perception of the roadmap for PEFC commercialization, the most critical issues in technological development, and the manner in which these three players should divide their roles. In addition, numerous relevant businesses are participating in a large number of government-led R&D projects, including the demonstration program being conducted by the Agency of Natural Resources and Energy and NEDO.

At this juncture, it is impossible to render a final judgment and assessment of the success of the aforementioned systems of cooperation and concerted action by the government, industry, and academia in developing PEFC technologies. Phase I of PEFC commercialization, aimed at platform development and the demonstration of technologies, is scheduled to last until 2005. If, at the end of this phase, the project strategies are properly re-assessed and the appropriate course adjustments made, this project will serve as a good model of a national innovation system.