Future Prospects and Public Policy Implications for Hydrogen and Fuel Cell Technologies in Canada

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Abstract:

The emergence of a fuel cell and hydrogen industry in Canada has been the result of a convergence of technological, industrial and market factors over the past decade and has been strongly influenced by environmental and innovation policy decisions at the local, federal and international levels. In the late 1990s Canada developed a world leading position in fuel cell and hydrogen technologies based in large part by advances in Proton Exchange Membrane fuel cell technology by Ballard Power Systems and a number of smaller highly innovative firms. This paper will provide an overview of the current state of the fuel cell and hydrogen industry in Canada and the near and mid term prospects for this industry in the transportation sector and well as the public policy implications and options the Canadian government must consider for future success.
Acknowledgements and Disclaimer

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The views expressed in this document are those of the author and do not necessarily represent the official position of the Government of Canada or the Office of the National Science Advisor.

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Introduction

The development, diffusion and widespread adoption of hydrogen powered fuel cells in both developed and developing economies has the potential for significant industrial, health and environmental benefits in terms of the emergence of a new, environmentally sustainable, knowledge-based industry; less dependence on fossil fuels; and decreased air pollution and greenhouse gas emissions. However, the commercial introduction of this technology into mainstream transportation, stationary power, and small appliance applications faces considerable technical, economic and infrastructural challenges that require public policy responses at the local, regional, national and international levels.

Fuel cells are highly efficient energy conversion devices that have the potential to replace or augment internal combustion engine and battery technologies in a wide range of applications. A fuel cell system is a fuel cell stack combined with balance-of-plant and other sub-systems to form a functional energy solution (a more detailed description of the technology can be found in Appendix 1).

Canada has been actively involved in the development of fuel cell technologies since the early 1980s. By the late 1990s Canada had achieved a world leading position in fuel cell and hydrogen technologies, based in large part by advances in Proton Exchange Membrane Fuel Cell (PEMFC) technology by Ballard Power Systems and a number of smaller, highly innovative firms. Today, there are an estimated 80 Canadian-based firms active in the sector. Ballard Power Systems (Burnaby, British Columbia) and Hydrogenics (Mississauga, Ontario) are the two largest fuel cell and hydrogen companies in Canada.

The following document provides an overview of Canada’s current positioning and future prospects in this emerging industry with a particular focus on the transportation sector as well as the range of policy and program support instruments in place to ensure the future viability of the industry and the successful integration of the technology into the Canadian energy system.

The discussion paper concludes with a series of observations on the technical, industrial and public policy options facing the industry.
Strategic Context

Energy Supply and Climate Change

The single most significant public policy driver for the eventual emergence of a hydrogen economy in the coming decades is best summed up by Richard Smalley: “Energy for 10 billion people”. By the year 2050, it is estimated that the world will require 10 TWs of installed capacity, or a new nuclear power plant every other day for the next fifty years (Smalley, 2005). The combined effects of skyrocketing demand for energy in China and India, with little excess production capacity and vulnerability of conventional oil supplies in the Middle East due to political instability and natural disasters will exert tremendous pressures on economies around the world. The International Energy Agency (IEA) predicts that the demand for primary energy will increase by 60% by 2030\(^1\). While 85% of the anticipated demand can be met by identified sources of fossil fuels, security of supply networks and rising extraction and transportation costs will be of major concern, particularly to developing countries with no indigenous fuel supply. The IEA estimates that the transportation will represent 65% of all energy demand by 2030 (Figure 1).

Figure 1

![Share of transport in total oil consumption, OECD 1971-2030](image)

Source IEA (2002)

Compounding these pressures is strong scientific evidence that global warming is occurring and is accelerated by anthropogenic factors. The earth’s temperature rose by 0.6°C over the past century and is forecast to rise between 1.4 and 5.8°C in the 21st century. Burning of fossil fuels coal, oil and gas is major contributor to carbon dioxide (CO\(_2\)) emissions and is the target of the UN Framework Convention on Climate Change and Kyoto Protocol which commits countries to reduce greenhouse gas emissions by 5% of 1990 levels by 2012. In April 2005, Canada released its plan for reducing greenhouse gas emissions by 270 megatonnes annually between 2008 and 2012\(^2\).

In this context of energy supply and demand scenarios and global commitments to reduce greenhouse gas emissions, alternative carbon-free energy will play an increasingly critical role in the international energy systems. As a clean, flexible energy vector obtainable from fossil, renewable and nuclear energy sources, hydrogen has recently assumed new credibility as a viable, longer term option to current energy options.

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\(^1\) International Energy Agency, *IEA World Energy Outlook 2004*

International Efforts in Hydrogen and Fuel Cell Technologies

After early stage development of fuel cell technologies for space applications in the early 1960s, fuel cell R&D activity accelerated in the last half of the 1990s driven by a number of factors including the announcement of low emission vehicle laws in jurisdictions such as California, the signing of the Kyoto Protocol, and dramatic advancements in PEMFC technology by Ballard Power Systems. Government support for Fuel Cell technologies is widespread throughout the OECD.

In 2003, The Bush Administration released a five-year $1.7 billion initiative to commercialize hydrogen powered cars by 2020, and the Japanese government doubled its R&D budget to $268 million. The European Union launched the first phase of a ten-year 2.8 billion Euro public-private partnership program to develop hydrogen fuel cells in 2004. In April 2004, the state of California announced a plan to establish up to 200 hydrogen fuelling stations along the interstate highways by 2010. *Fuel Cell Today* estimates there were over 310 fuel cell vehicles on the road around the world in 2003, with the projected number to reach 520 by the end of 2005. Some 100 hydrogen fuelling stations were in operation in 2004. Ballard Power Systems is one of the major suppliers of fuel cells to these markets as well as GM, Toyota and UTC Fuel Cells. A review of the US Patent Office Database revealed 3,337 fuel-cell related registered patents between 1860 and 2002. Ballard is one of the top ten patent holders in fuel cells and among the top in the world in PEMFC technology (Table 1).

| Table 1: # of Patents per company or organization in fuel cell patent database |
|---|---|
| 1 | United Technologies Corp. | 159 |
| 2 | United States of America | 139 |
| 3 | International Fuel Cells | 133 |
| 4 | General Electric Company | 102 |
| 5 | Westinghouse Electric Company | 88 |
| 6 | Leesona Corp. | 85 |
| 7 | Seimens Aktiengesellschaft | 84 |
| 8 | Union Carbide Corporation | 72 |
| 9 | Exxon Research and Engineering | 68 |
| 10 | Ballard Power Systems Inc. | 58 |
| 15 | General Motors Corporation | 48 |
| 16 | Plug Power Inc. | 47 |

Source: Verspagen (2005)

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3 *Fuel Cell Today*, 21 April 2004
4 *Fuel Cell Today*, 5 May 2004
The 2005 Worldwide Fuel Cell Industry Survey shows a slowing growth in 2004 in terms of revenues (a 4% decrease from $244M US in comparison with 2003)\(^5\). Canada ranks first in the world in revenues ($135M) followed by the US. R&D expenditures grew to $221 million from $216 million in 2003. Canada ranks first in the world in R&D at $115 million, following the US, which represents 52% of the survey.

The market focus for the fuel cell industry is fairly equally distributed across six major market segments (Figure 2). The technology focus is dominated by PEM fuel cell technology (56%) followed by Solid Oxide Fuel Cells (SOFC) (18%) (Figure 3).

Market forecasts vary considerably from SRI Consulting (2005), which forecasts a $48 billion market demand for fuel cells by 2013, dominated by portable power applications (50%) followed by transportation and stationary power applications at roughly 25% each and ABI which sees more modest growth of closer to $18 billion by 2013.

Despite the growth in R&D and technological development in fuel cell technologies in recent years, considerable technical and economic barriers remain before mainstream commercialization of the technology, particularly in the transportation market, where in the words of the National Research Council and National Academy of Engineering, “fuel cell prototype costs are still a factor of 10 to 20 times too expensive and these fuel cells are short of the required durability”.\(^6\) For mass market automotive uses, the cost targets for fuel cell systems in a vehicle must be well below $100/kw. Conventional internal combustion engine systems average $30/kw. Key technical and economic challenges remain in the cost of materials for the fuel cell stack; hydrogen transport, storage capacity and cost; access to hydrogen fuelling infrastructure; and performance requirements.

\(^5\) PricewaterhouseCoopers – 2005 Fuel Cell Industry Survey. Note, the survey is restricted to publicly owned companies which represent approximately 1/3 of the industry and does not include subsidiaries of large diversified corporations such as UTC Fuel Cells and Rolls Royce Fuel Cells.

Overview of Canadian Fuel Cell Industry and Innovation system

History

Canada has been an active player in fuel cell technologies from the early 1980s, driven in part by the National Research Council’s (NRC) Hydrogen and Energy Storage Program, and strong linkages to the University of Toronto. After the shutting down of the NRC Energy Research Program in 1985, the majority of federal fuel cell and hydrogen technology development support was taken up by the Ministry of Energy Mines and Resources.

A key milestone in the development of fuel cells in Canada was a procurement contract issued to Ballard Power Systems by the Department of Defence in November 1983, for a small PEM fuel cell stack. Geoffrey Ballard, a Canadian who had worked in the US Department of Energy in the 1970s had set up a small company in Vancouver in the early 1980s. The remarkable technical achievements by Ballard in PEM stack power density over the course of the following ten years (Figure 4) not only established Ballard as a leading player in this technology but also ignited a renewed interest in pursuing the technology. In 1999 Ballard Power Systems signed strategic alliances with DaimlerChrysler and Ford for fuel cell automotive engine development. It received the first major fuel cell bus demonstration contract by the Chicago Transit Authority in 1998. By 2000, driven in part by the Ballard strategic alliances, virtually every major car manufacturer in the world had developed a technical alliance with a fuel cell producer or had established its own in-house development program.

In Canada, a number of other companies also emerged during this time period. Stuart Energy Systems (Mississauga, Ontario), a well-established hydrogen energy station manufacturer; and Hydrogenics (Mississauga) initially specializing in hydrogen testing and refuelling equipment. Global ThermoElectric, a Calgary-based firm, entered into the Solid Oxide Fuel Cell (SOFC) stationary power market in the late 1990s. Other supply firms such and Dynetek, (hydrogen storage) and QuestAir (hydrogen purification), became important players in the Canadian fuel cell and hydrogen industry.

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9 In February 2005, Stuart Energy Systems was acquired by Hydrogenics.

10 Global Thermoelectric was sold to Versa Power, a US-based firm in 2004.
Canadian Fuel Cell and Hydrogen Industry

In 2004 there were an estimated 83 organizations in Canada involved in the fuel cell sector in Canada including, professional service providers, suppliers, research organizations. Seventeen companies across Canada are fuel cell producers and/or systems integrators. Of that total, 51% have been active in the sector for less than 5 years (Figure 5).

The Canadian industry recorded $188 million in sales in 2003, up 40% from the previous year, while R&D expenditures were estimated to be $290 million, an increase of 5% from 2002 (Figure 6).

11 Canada’s Fuel Cell and Hydrogen Industry Capabilities Guide (04/05)
The technology focus of the Canadian industry mirrors that of the global sector in that over half of the sector is focused on PEMFC, followed by SOFC and, to a lesser extent, Direct Methanol Fuel Cells (DMFC).

The Canadian industry primary market focus is concentrated on stationary applications as is the case in other jurisdictions, but differs from the international trends in that there is a greater interest in fuelling infrastructure in Canada (28%) than the international average (14%); and in transport applications (24% in Canada compared to 14% internationally) as noted in Figure 3.

The survey reported a significant (232%) increase in participation by Canadian organizations in demonstration projects from 2002 to some 262 projects around the world, 69% of which were outside of Canada (Figure 7).

The Canadian fuel cell and hydrogen sectors are supported by two industry associations.

- Fuel Cells Canada ([www.fuelcellscanada.ca](http://www.fuelcellscanada.ca)), based in Vancouver British Columbia was established in 2001 in order to promote the Canadian fuel cell industry in Canada and internationally and in Canada as well as facilitating demonstration projects for testing and pre-commercial development.

- Canadian Hydrogen Association ([www.h2.ca](http://www.h2.ca)), based in Toronto with offices in Montreal, Ottawa and Trois-Rivières is a non-profit membership driven association composed of universities, research organizations, industry and small business with the objective of promoting the use and development of hydrogen energy, energy systems and technologies for the purpose of improving the environment.
Federal Support Programs

The Canadian federal government has a wide array of policy and program instruments that are either directly or indirectly targeted at promoting the emergence and global market penetration of Canadian fuel cell and hydrogen technologies. These measures cover the spectrum from basic and applied R&D to market development support, risk financing, standards development and market demonstration projects.

Policy

Policy support for fuel cells and hydrogen technology cuts across the mandates of several federal ministries. The Minister for Natural Resources and the Minister of the Environment provide policy direction for energy, environment and sustainable development policy in Canada. The Minister of Industry is the federal government’s lead Minister for industrial and regional development policy. Hydrogen and fuel cells have potential policy implications for virtually every ministry under federal jurisdiction from transportation, aboriginal affairs, international trade, defence and health and safety.

In 2004 a special ad hoc committee of Cabinet, Sustainable Development and Economic Prosperity was created, chaired by the Minister of Industry with the participation of the Ministers of the Environment, Natural Resources and other ministries as required to ensure policy coordination and coherence on a wide range of issues including climate change and alternative energy.

In February 2005 the federal government announced its intention to develop a Sustainable Energy Science and Technology Strategy by the end of 2006 along with a commitment to dedicate $200 million to the development and implementation of the strategy. This process is being led by the Minister of Natural Resources.

Policy and program coordination are ensured within the federal government through the Hydrogen and Fuel Cells Committee co-chaired by Industry Canada and Natural Resources Canada with a mandate to develop, implement and maintain a long-term national strategy for the development of fuel cell technology and the transition to a hydrogen economy.

Key Institutions

Natural Resources Canada’s (NRCan) Alternative and Future Transportation Fuels Program, Supports the use, development and production of alternative transportation fuels such as ethanol, natural gas and hydrogen fuel cells. It also provides public education, economic and market analyses, research of standards and harmonization of policies. NRCan has a number of program instruments in place through either direct performance of R&D in support of fuel cell and hydrogen they include:

- Canadian Transportation Fuel Cell Alliance (CTFCA) created in 2000 with $33 million in funding over seven years. By 2004-05, $17 million had been allocated to projects including fuelling station prototypes, fuel cell vehicle development, hydrogen storage, hydrogen dispenser systems and national and international codes and standards.
CANMET Materials Technology Laboratory;
Hydrogen and Fuel Cell R&D Program;
NRCan Industry Energy Research and Development (IERD); and
Process and Environmental Catalyst Program.

**Technology Early Action Measures (TEAM).** Is a federal interdepartmental technology investment program, co-managed by NRCan, Environment Canada and Industry Canada, created under the federal government’s Climate Change Action Plan. TEAM supports projects that are designed to develop technologies that mitigate greenhouse gas (GHG) emissions nationally and internationally, and that sustain economic and social development. TEAM has a portfolio of projects in five areas:

- Cleaner fossil fuels;
- Energy-efficiency technology;
- Biotechnology;
- Hydrogen economy; and
- Decentralized energy production.

The program focuses on projects at the demonstration phase of the commercialization process where funding and technical assistance is scarce when preparing to bring a new technology to market following the end R&D activities. Projects are assessed on the ability to meet stringent technical and emissions performance criteria, which provide the risk financing sector with a degree of understanding and confidence in the potential viability of the technology in future market applications.

**Industry Canada’s** Energy and Environment Industries Branch is presently engaged in a number of activities related to the development and commercialization of hydrogen and fuel cell technologies. These activities include: increasing access to investment capital and promoting international strategic partnerships; addressing technical barriers to distributed generation; and, facilitating commercialization roadmaps.

Industry Canada is also responsible for the delivery of **Technology Partnerships Canada (TPC)**, which provides loan support for high-risk, pre-commercialization research for product and process development. In 2003 TPC created the Hydrogen Early Adopters Program with $50 million over five years to support up to 50% of eligible costs of hydrogen and fuel cell projects. Recent investments include approximately $9 million each to both Cellex and General Hydrogen for R&D activities focused on commercialization of fuel cell fork lift trucks. In 2004-05 $13.3 million was awarded to four projects involving 32 Canadian organizations.

Regional development priorities are delivered through four federal regional development agencies (Western Economic Diversification, Federal Northern Economic Development, Canada Economic Development for Québec and Atlantic Canada Opportunities Agency).

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12 On September 20 2005, the Minister of Industry announced the restructuring of TPC and the creation of Transformative Technology Partnerships (TTP).
The National Research Council (NRC), as the federal government’s primary R&D performer and industrial research support agency identified fuel cell and hydrogen technologies as a strategic priority in 2000 with the launching of the Fuel Cell Technologies Program, and the establishment of the NRC Institute for Fuel Cell Innovation in 2002 in Vancouver, British Columbia. NRC’s Institute for Chemical Process and Environmental Technologies has also been heavily involved in fuel cell R&D for several years. In addition to R&D collaborations with industry, NRC’s Industrial Research Assistance Program (IRAP) provides R&D funding and technical assistance to small and medium sized enterprises (SMEs) and in 2001 partnered with Technology Partnerships Canada to deliver a pre-commercialization R&D loan program targeted at SMEs.

NRC’s Fuel Cell program is also the result of the organization’s technology cluster strategy, whereby NRC investments and activities are focused on ensuring the emergence of competitive technology clusters in Canada. Vancouver and the lower B.C. Mainland were seen as an emerging cluster in fuel cells where NRC expertise could best be focused. NRC has received three rounds of funding since 2001 to implement its clustering strategy in ten communities across Canada.\(^{13}\)

The Natural Sciences and Engineering Research Council (NSERC) provides direct research funding to Canadian universities in basic and applied R&D. A number of NSERC program initiatives support applied research in fuel cell and hydrogen technologies including:

- Collaborative Research and Development (CRD) Program;
- Ideas to Innovation (I2I) Program;
- Industrial Research Chairs; and
- Strategic Project Grants.

In 2003-04, NSERC invested $1.4 million in hydrogen related research and $3.6 million in fuel cell research for a total of $5 million across all NSERC Programs. In 2002-03 NSERC investments totalled $3.1 million. NSERC currently funds five Industrial Research Chairs in hydrogen and fuel cell technologies.\(^{14}\)

The Networks of Centres of Excellence (NCE) Auto21 Program was formed to focus Canadian research expertise on the task of improving and enhancing the global competitiveness of the Canadian automotive industry. The Network currently supports over 230 top researchers working at more than 37 academic institutions, government research facilities and private sector research labs across Canada and around the world. Auto21’s Powertrains, Fuels and Emissions research program currently funds four projects focused on automotive applications:

- Chemical Hydrogen Storage Process Development;

\(^{13}\) [http://www.nrc-cnrc.gc.ca/clusters/index_e.html](http://www.nrc-cnrc.gc.ca/clusters/index_e.html)
\(^{14}\) For a listing of the Industrial Research Chairs, see: [http://www.nserc.gc.ca/partners/chairs_e.asp](http://www.nserc.gc.ca/partners/chairs_e.asp)
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- PEM Fuel Cells and Related Technologies;
- Hydrogen Safety and Infrastructure Study for Hydrogen Vehicles; and
- On-Board Fuel Cell Powered Auxiliary Power Units

Under the Societal Issues Program, Auto21 also funds a project entitled *Automotive Industry-Government Relations in the 21st Century*, which looks into the public policy implications of Canada’s ability to participate in a hydrogen-based economy, given its early strengths as a leader in this technology; and *Evolution of Life Cycle Assessments*, and how LCA tools can be integrated into decisions regarding design, manufacturing, and end-of-life in the auto sector.

**National Defence** (DND) through R&D, demonstration and procurement the key programs affecting fuel cell and hydrogen technologies include:

- Industrial Research Program;
- Defence R&D Canada; and
- Technology Demonstration Program.

**Sustainable Development Technology Canada** (SDTC) was created in 2001 as an arm’s-length funding organization to foster the rapid development, demonstration and pre-commercialization of technological solutions that address climate change and improve air quality. Funding is dependant on the formation of sound partnerships involving the key elements of the innovation chain—including private sector, academia, government, and not-for-profit organizations. SDTC will fund up to 33% of an eligible project. Examples of recent SDTC funded projects include:

- **Cellex Power Products, Inc.** Fuel cell–based power products for use in industrial vehicles. This project focuses on demonstrating a fuel cell–powered forklift. Cellex aims to assemble Cellex Fuel Cell Power units for commercial use by the end of 2005.

- **Sacré-Davey Innovations Inc.** Development and demonstration of a hydrogen fuel refining, storage, distribution and infrastructure program for power generation, heavy and light-duty hydrogen burning vehicles, and vehicle refueling technologies.

- **Hydrogenics Corporation.** Develop, demonstrate, and commercialize fuel cell–powered forklifts. This would involve outfitting two Class-1 forklifts with motors and fuel storage systems, as well as developing refueling facilities and demonstrating the newly outfitted forklifts to industrial end users.

**Provincial Strategies and Programs**

Over the past decade, Provinces across Canada have focused on fuel cell and hydrogen technologies to varying degrees. Québec has focused primarily on the hydrogen sector because of its considerable hydro-electric resource capacity and the potential synergies with the growing natural gas sector in the province. Centres of expertise especially at the University du Québec à Trois-Rivières, INRS Énergie and Hydro-Québec have become the primary platforms for hydrogen technology R&D and demonstration in the Province.
The Government of British Columbia has been particularly proactive in developing a hydrogen and fuel cell strategy for the Province. With the largest single concentration of fuel cell producers, system and component suppliers, research institutions, and as the headquarters for Ballard Power Systems, the B.C. Lower Mainland is one of the most developed fuel cell clusters in the world. In 2003 the B.C. Premier’s Technology Council released a four-part industrial strategy for the Province in Hydrogen and Fuel Cells technology.

- Securing Global Leadership;
- Developing our World Markets;
- Investing in our Knowledge Base; and
- Sustaining our Resource Based Sectors.

The vision driving the strategy for the Province is to have the world’s pre-eminent hydrogen economy by the year 2020. The centrepiece of the strategy is the Hydrogen Highway project for the 1010 Winter Games to be held in Whistler B.C. This event will be an international showcase for the demonstration of a viable integrated multimodal hydrogen system linking the Vancouver Airport to Whistler.

In Ontario, the provincial government launched a clean energy strategy and a hydrogen and fuel cell demonstration program ($3M annually for five years).  

### Issues for Canadian Fuel Cell Development

The future prospects for the emergence of a viable and competitive fuel cell industry in Canada are similar to those of other science-based industries such as biotechnology, nanotechnology, and advanced materials. While each of these industries have issues that are specific to their own sectors, they share similar obstacles in terms of high levels of technological and scientific uncertainty, long gestation periods for commercial development, difficulties in securing appropriate risk financing, lack of established markets and complex regulatory issues. Often firms in these industries are characterized by small, undercapitalized start-up firms with high levels of R&D expenditures and limited if any revenue streams. The following section provides an overview of a range of issues and challenges facing the fuel cell sector in Canada and around the world.

#### Cost

The most significant barrier facing the fuel cell sector market penetration remains the considerable cost disadvantage of fuel cell and hydrogen storage and distribution against established alternatives in the market today. In the case of transportation markets, the gasoline powered internal combustion engine has a cost-per-unit advantage several orders of magnitude above fuel cell technologies. Passenger cars typically cost $30/kW while PEMFC prototypes are estimated by the NRC to be 100 times more expensive at current low volume production levels.

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15 [http://www.ontariocanada.com](http://www.ontariocanada.com)
The cost issues can be broken down in terms of materials, hydrogen transport, storage and compression, and volume manufacturing. While the first two elements are technical and engineering issues, volume manufacturing is a market-driven condition. The production of novel fuel cell power sources in autos and other transportation applications much reach levels of millions of units per year, in hyper-competitive automotive markets where profit margins are razor thin. Most analysts predict that the fuel cell industry is decades away from competing head to head with consumer auto manufacturers.

**Technical**

Technical issues associated with fuel cell development are related to materials use, engineering and functionality, durability, engine performance, and hydrogen storage and compression.

As an example of company strategies in addressing these issues, Ballard Power Systems recently released a Technology Road Map\(^\text{16}\) outlining the technology development results and performance targets for 2010 in four areas considered to be of critical importance for commercializing PEMFCs in the automotive market.

- **Durability** – Ballard’s durability target of > 2,000 hrs. with a 10-cell stack was achieved in 2004 (representing the equivalent of over 100,000 Km under normal driving conditions). The company claims to be on target to meet the US Department of Energy goal for durability of 5,000 hrs. by 2010.
- **Freeze Start** – Ballard demonstrated successful starts at -20°C in under 100 seconds and is targeting -30°C at under 30 seconds by 2010.
- **Power Density** – Ballard’s is expected to reach a 1,400 Watts\(_{\text{net}}/\text{litre}\) power density milestone later this year that would put it ahead of schedule for meeting the DOE goal of 2,000 W\(_{\text{net}}/\text{l}\) by 2008 and reaching a target of 2,500 W\(_{\text{net}}/\text{l}\) by 2010.
- **Cost** – Ballard announced a 30% reduction in platinum catalyst loading for the new stack design, resulting in significant material cost reductions without performance losses. Its current estimates of stack production using a volume manufacturing scenario of 500,000 units/year are below $100/kW and will put it on track to meet the DOE goal of $30/kW by 2010.

Progress against these benchmarks over the coming five years will be of critical importance to the company’s prospects of commercializing its fuel cell technology in the automotive sector and reassuring its investors of the technical and economic viability of the technology.

Hydrogen technical challenges are primarily focused around transport, storage and compression issues. Onboard reforming of methane or natural gas was an option considered by a number of fuel cell system developers in the mid 1990s but has all but been discounted in the industry as a viable solution. Because hydrogen is a light diffuse

gas it is difficult to store on board and give it adequate range between fuelling. Large-scale storage and transportation for example is estimated require over 21 times the storage capacity than that of conventional gasoline.\textsuperscript{17} Calgary-based Dynetek Industries is one of the world’s leading developers and suppliers of advanced lightweight composite pressure vessels. Research into solid state hydrogen storage solutions based on metal or chemical hydrides and carbon nanotubes is one area being actively pursued by a number of Canadian universities.

If PEMFCs are to be successful in the automotive market, hydrogen purity will be a critical performance factor. Existing PEM designs require 99.999% hydrogen purity, which is a much higher level than that required by other fuel cell technologies such as SOFC used in stationary power applications, or by hydrogen-powered internal combustion engines. Carbon monoxide traces of less 10 parts per million can poison the PEM catalysts. Given that CO is a by product of fossil fuel-based hydrogen production, purification technologies such as Pressure Swing Adsorption, such at that developed by Vancouver-based QuestAir will be an important to the future commercialization of the technology.

**Infrastructure**

Hydrogen infrastructure access, availability and safety will be a fundamental condition for the growth of fuel cell applications in transportation markets. Canada is the largest per capita producer and user of hydrogen in the OECD at about 2.88 million tons per year, of which over 90% is produced in western Canada. Global hydrogen production has increased at a 5% per annum rate over the past 10 years and is expected to continue growth at the same rate for the next ten years. Should fuel cells be successful in penetrating the automotive and transport sectors in the coming decade, the rate of growth for hydrogen demand would increase exponentially.

While hydrogen has notable performance attributes over hydrocarbons in terms of efficiency, emissions, and range of applications, it does not travel well because of its low volume density, high cost of production and transport and public concerns over safety. There are currently five large scale compressed hydrogen storage facilities in Canada, situated near production sites. There are a limited number of fuelling stations located in testing and demonstration sites in Vancouver, Victoria, Toronto, Ottawa, Trois-Rivères and Prince Edward Island.

**Marketing**

Market penetration strategies vary from company to company. The industry will inevitably take a staged process of applications based on cost competition and the availability of alternative energy sources. Most marketing studies point to small stationary power applications and appliances as short-term market opportunities. In the medium term, various niche applications in the transportation sector include specialized industrial equipment, lift trucks, mining vehicles, urban bus fleets and car fleets.

\textsuperscript{17} DALCOR (2004) p. 1.3.
A study by Methanex Corporation in 2002 sees the current capital cost-per-kilowatt benchmark of $10,000/kW only competitive in remote off-grid sites for stationary power applications. The current automotive benchmark of $30/kW is seen as being at least 12 to 15 years away, and is considered to be at best an optimistic scenario because it does not assume improved cost efficiency in the auto industry.

Estimates based on three government policy scenarios developed by DALCOR Consultants see market penetration in the passenger, fleet and urban transit markets ranging considerably between 2015 and 2023 (Table 2).

![Table 2: Fuel Cell and Hydrogen Demand Projections 2023](image)

In Canada, Ballard Power Systems remains primarily focused on automotive applications as its core market strategy. Alliances with Ford and DaimlerChrysler have provided access to key marketing and manufacturing capabilities. Other firms such as Palcan, Hydrogenics and Cellex are targeting niche market for small <25kW applications such as scooters, pleasure craft, and forklifts.

**Risk Financing**

Access to risk capital was identified by the fuel cell industry as a major impediment to commercialization. According to the Fuel Cell and Hydrogen Industry 04/05 Capabilities Guide expected domestic financing by source of funding is $957 million from 2005-2010 in the Canadian fuel cell sector where 14% will be from private equity ($133.98M). The BC fuel cell sector has raised $239.7 million in Venture Capital over the past four years. Large institutional investors in Canada such as large pension funds have traditionally had much lower exposure to high tech start ups than their counterparts in the US. In Canada it is estimated that technology ventures represent less that 2% of pension fund holdings while in the United States pension fund technology venture investment represents 11% of institutional portfolio holdings.

Long gestation periods and lack of adequate financing instruments for fuel cell companies can severely handicap start-up firms that face huge development and

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marketing costs. The “valley of death” analogy, as represented in Figure 8 from Sustainable Development Technologies Canada, is typical in this industry.

Policy and government support for risk financing in high technology industries is primarily driven through the tax system where the Scientific Research and Experimental Development tax credit program is considered to be among the world’s most generous and effective tax credit programs estimated at over $1.2 billion. However SR&ED tax credits are focused on R&D and are redeemable against revenues, which for many early stage firms in the industry with limited or non-existent revenue streams creates severe cash flow problems.

**Figure 8 – Risk Financing Spectrum**

Other risk financing instruments for Canadian firms include the Business Development Bank seed and venture capital investments that focus on higher risk technology ventures that are normally beyond the risk parameters of many private sector investors. Programs such as TEAM, SDTC, TPC, and NRC-IRAP provide varying levels of risk financing in the form of grants or repayable loans at the pre-competitive stage.

The question of access to capital and early stage risk financing has been a subject of considerable debate in Canada over the years and in currently a key focus of a Commercialization Expert Panel, commissioned by the Minister of Industry David Emerson in June 2005, and chaired by Joseph Rotman. Among options being proposed to the Panel include:

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20 The Rotman Committee is expected to release its final report in fall of 2005
Future Prospects and Public Policy Implications for Hydrogen and Fuel Cell Technologies in Canada

- Flow-through share financing provision, which is currently used in the mining and oil exploration sectors, and promoted by Fuel Cells Canada and Ballard Power Systems;
- An angel investor tax credit program modeled after the B.C Industrial Innovation and Productivity Tax Credit proposed by the National Angel Organization;
- An expansion and modification of the Federal SR&ED Tax credit system to include downstream development activities and reduce restrictions to publicly traded companies.

Future Prospects and Outlook

A key development in the industry in Canada and internationally in recent years has been to shift from small bench and laboratory demonstration projects to larger integrated hydrogen system projects. These demonstration projects provide the basis for testing and evaluating fuel cell and hydrogen technologies in an integrated interactive system that includes transport, stationary applications with hydrogen transport, storage and refuelling platforms. These projects also provide a more high profile exposure and general public awareness.

Demonstration and Systems Integration Projects

In Canada there are currently a number of projects of this nature under development.

Hydrogen Highway – Olympics 2010

On April 1, 2004, at GLOBE 2004, Prime Minister Paul Martin announced Canada’s plans to build a Hydrogen Highway from the Vancouver Airport to Whistler for the 2010 Winter Olympics.

The Hydrogen Highway is a coordinated, large-scale demonstration and deployment program intended to accelerate the commercialization of hydrogen and fuel cell technologies. It consists of seven nodes – each with plans for its own sustainable microcosm with hydrogen fueling infrastructure as well as a range of transportation and stationary applications (see figure 9 for outline).

By creating an early adopter community of technology developers and users throughout British Columbia, the Hydrogen Highway will play an integral role in removing barriers for hydrogen and fuel cell commercialization. The project will develop a critical mass of expertise, knowledge, and experience in the area, provide data for developing international codes and standards
around implementing the technology, stimulate demand for the technology by allowing the media and general public to feel, touch and see the benefits of a hydrogen economy, open doors for international partnership and create a hydrogen infrastructure legacy in association with a high profile international event.

The original key partners for the development of the Hydrogen Highway concept are Methanex Corporation, BC Hydro and the NRC Institute for Fuel Cell Innovation (NRC-IFCI). With the July 2003 announcement that Whistler would host the 2010 Winter Olympics and that the Games would have a strong focus on environmental sustainability, the project had the opportunity to demonstrate the viability of a hydrogen economy system on a high profile international stage. Since then, Industry Canada and Natural Resources Canada have committed substantial funding toward fuel cell and hydrogen research and demonstration projects. The Province of British Columbia has become a champion of the concept, viewing it as a metaphor for the transition to the hydrogen economy. It is, in fact, the backbone of the BC hydrogen and fuel cell strategy document. Examples of projects that will be implemented for the Hydrogen Highway include:

- A hydrogen fuelling station and storage tower that will power several Ford Focus Fuel Cell Vehicles. Hydrogen will be generated by an electrolyser on site at NRC-IFCI;
- A sustainable energy system – photovoltaic panels will produce solar energy to power an electrolyser and generate hydrogen for a fuel cell that will provide backup power to the new NRC-IFCI building;
- A solid oxide fuel cell will provide heat and power to NRC-IFCI;
- Hydrogen-fuelled internal combustion engine vehicles, hydrogen-enriched natural gas powered vehicles and hydrogen-powered generators at UBC; and
- Sustainable residential community feasibility studies and development in the surrounding area at UBC.\(^{21}\)

BC Transit has put a proposal to government for the purchase of 20 fuel cell buses for the 2010 Olympics which would be driven for up to 16 years.

**Hydrogen Village**

Spearheaded by the University of Toronto Mississauga’s (UTM) Centre for Emerging Energy Technologies, Hydrogenics and the City of Toronto authored a Framework Document that gave substance to the Hydrogen Village (H2V) concept in the Greater Toronto Area. Now with close to 40 members, the Partnership is a pioneering collaboration of industry, government, and the academy that is determined to accelerate the commercialization of hydrogen and fuel cell technology in Canada\(^ {22}\).

Federal granting programmes that provide financial support for the development of fuel cell and hydrogen technologies are already encouraging prospective applicants to pass their project proposals through the H2V for review, comment and endorsement.

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\(^{22}\) [http://www.utm.utoronto.ca/1560.0.html](http://www.utm.utoronto.ca/1560.0.html)
As a leader in the Hydrogen Village and a member of the Village’s Oversight Committee, UTM’s Centre for Emerging Energy Technologies has three projects in this partnership currently under federal review:

- Fuel Cell Emergency Power Supply; and
- Hydrogen (ICE)-Battery Hybrid Hybrid bus – Partners: UTM, Stuart Energy, BET Services, and the City of Mississauga.

Hydrogen Corridor

The Québec-Ontario Hydrogen Cooperative is planned as a bi-provincial network of innovative communities that traverses Canada’s industrial heartland. The mission of the Hydrogen Corridor Cooperative is to accelerate the integration of a sustainable hydrogen economy through the synergy of hydrogen and fuel cell community initiatives within the region. The Québec-Ontario Hydrogen Corridor Cooperative will essentially be realizing the Hydrogen Age. It will be a concentration of interconnected municipalities, companies, specialized suppliers, service providers, firms in related industries, and associated institutions (universities, standards organizations and trade associations) linked by commonalities and complementarities that cooperate in the hydrogen and fuel cell sector to facilitate the deployment of the Hydrogen Economy. It will also serve as a focal point for public outreach and awareness and will be a driver for broad market acceptance of hydrogen and fuel cell products in the region. It is designed to be a sustainable collaboration of communities for the introduction of greenhouse gas reducing technologies, strengthening the Canadian hydrogen and fuel cell energy technology companies and create new ones.

Large Fleet Demonstration and Early Adoption Programs

From the perspective of transportation applications and introduction to the automotive markets, the federal government is concentrating on large fleet applications and in particular urban transit applications where early stage economies of scale can facilitate investments in hydrogen infrastructure and fuel cell technology platforms.

Urban Transit Bus Fleets

In January 2005 the government of Canada through the Canadian Transportation Fuel Alliance released a major study on the socio and economic viability and policy issues with respect to the integration of Hydrogen-Powered Fuel Cell Technologies in Canadian Urban Transit Systems (UTS). Canadian Urban Transit bus fleets are currently powered almost exclusively by diesel, and are a natural early adopter of hydrogen fuel cell technology that can reduce greenhouse gas emissions and urban air pollutants to zero. The study points to key factors and benefits to adoption in this sector and provides 50


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recommendations to the UTS industry, bus manufacturers, fuel cell system suppliers, Hydrogen Storage system suppliers, Hydrogen Fuel and Fuelling system providers, training institutions and governments.

The Canadian urban transit systems are an ideal sector to engage because:

- There are over 2.42 billion riders per year;
- The number of vehicles – approximately 12,000 across Canada – is a sizeable market;
- UTSs consume over 360 million litres of diesel and 17 million cubic meters of natural gas per year;
- The transit application is visible to a public sympathetic to improving air quality;
- Transit properties have a centralized infrastructure that can be adapted to hydrogen; and
- Urban transit applications have global market relevance.

The study notes in particular that in contrast to the US, where the US Department of Transportation Federal Transit Administration can fund up to 80% of the capital costs of transit buses, no similar program exists in Canada to facilitate transition costs. “While fuel cell-powered buses are expected to be cost-competitive on a lifecycle basis, the cost of acquisition (anticipated to exceed that of a diesel bus by two-thirds) is more than most urban transit systems can afford. As well, the one-time cost of adapting facilities, tooling, and equipment is outside the normal scope of transit system budgets. While this transition is feasible, it will require new arrangements with funding partners to ensure that additional support for capital costs is available.”

Conclusions

Canada’s current and potential future positioning as a key player in the development and commercial application of Fuel Cell and Hydrogen Technologies is an important case study for Canadian S&T Policy because of a number of factors:

- It is a strategic emerging technology with a broad applications in a number of industries;
- It is at the interface among a wide range of public policy priorities including environmental sustainability, climate change, energy use and conservation, transportation planning, industrial and regional development;
- It is a high-stakes industrial issue where the eventual securing of major market segments in the automotive, stationary and portable power markets could represent billions in terms of export revenues, and domestic energy savings; and
- It is a sector where close policy coordination at the municipal, provincial, federal and international levels will be of critical importance to the future success of the industry and technology.

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As a small, export-dependant economy with few large-scale multinational firms in technology intensive industries, government strategy aimed at ensuring that the benefits of the future adoption of fuel cell and hydrogen technologies are accrued to Canada will be of critical importance. Canada’s early technological lead in this field developed over the 1990s by Ballard Power Systems and the emergence of new technology intensive SMEs in this sector clustered around the lower B.C. Mainland and the Greater Toronto Area could be lost.

Given developments in Canada and internationally in fuel cell and hydrogen technologies, the short to mid-term prospects for the successful commercial introduction are limited. A Canadian strategy must include the following elements.

**Research support**

Fundamental research issues associated with cost, performance and materials use must continue to be addressed by the academic and government research sector in close collaboration with Canadian industry. These efforts must be linked to international programs such as the International Partnership for the Hydrogen Economy, the European Framework Programs and the US Department of Energy. Research must also increasingly integrate social science perspectives including economic, social, environmental, health, cultural and ethical dimensions because of the significant public policy implications.

**Commercialization**

Different technologies within the sector are at different stages of development processes. Support for commercialization of niche applications will help solve technical and market issues, build hydrogen-fuelling infrastructure and accelerate full-scale commercialization of automotive applications. The Government of Canada is following this hypothesis and providing support through its various programs to companies involved in early applications such as fork lifts, material handling, uninterruptible power supply and micro applications.

As transformative technologies, fuel cells will take time to develop, be integrated into commercial products, and gain acceptance in the marketplace. Development of the fuel cell sector will require processing through the various stages of industry development from basic R&D to applied R&D/product development to testing/engineering and development of codes and standards, demonstration, market demonstration, and production and sales. Issues at any one of these stages can slow the overall commercialization process. Support for commercialization of niche applications will help solve technical and market issues, build hydrogen fuelling infrastructure and accelerate full-scale commercialization of automotive applications.

Support for the Hydrogen Economy related stages of commercialization and the government’s ability to share risk with technology developers with good ideas and end users willing to adopt new solutions will continue to help move companies to proof of concept stage and attract large partners and investors which are key in their transition to market ready profitable companies. Key to Canada’s success will be government’s ability
to bring together various players in the planning, development and implementation of key strategies, initiatives and projects to address commercialization through the innovation continuum.

**Risk financing support**

Given the long gestation and development timelines for fuel cell and hydrogen technologies, and in other emerging industries such as biotechnology, non-market distorting, pre-competitive risk financing instruments through the tax system or government backed risk financing must be looked at more thoroughly. The Canadian SR&ED tax credit system does not serve technology intensive SMEs with little revenue cash flow. The Rotman Expert Panel, commissioned by the Minister of Industry is expected to address this issue in the coming months.

In light of the small size of Canadian companies in this sector, their limited access to financing, the long development times associated with commercialization and strong international competition, government support will be required to enable the industry to undertake the needed R&D, demonstration and deployment of technologies, develop partnerships and strategic alliances and accelerate the timelines to commercialization.

**Demonstration and Early Adoption**

In the coming years, governments at all levels will be shifting away from small scale single technology demonstration projects in highly controlled conditions to larger scale, integrated demonstration platforms that cover complete hydrogen system and fuel cell technologies for a wide range applications. These high profile projects will not only provide valuable technical information from a systems integration perspective, they will also be an important factor in promoting public awareness on economic, environmental and safety. From this perspective, the 2010 Winter Olympics will be a critical milestone for the future prospects of this industry in Canada. Should it succeed the credibility of the technology and the viability of the industry will be greatly enhanced. The potential for extending the hydrogen networks elsewhere in Canada and south to the United States will be the logical next step for the industry.

Over 60% of world hydrogen transportation demonstrations projects have Canadian participation. The Canadian government and the provinces have been instrumental in establishing some the world’s first integrated large scale demonstration projects such as the Hydrogen Highway and Village. Expansion of Canadian demonstration projects will enable Canadian companies to partner together with government and research organizations, to learn from real world conditions, in order to refine R&D priorities, develop expertise in hydrogen safety, testing methods and protocols, certification procedures, and analytical and experimental analysis to develop appropriate codes and standards for installations. This will help Canada in its current position of secretariat for the ISO Hydrogen Code.
Cluster Development and Linkages

From the perspective of technology based cluster development, three foci have emerged across Canada with a concentration of industry, technical expertise and sectoral linkages. The Lower B.C. Mainland remains the pre-eminent fuel cell cluster in Canada, with a wide range of technical and industrial linkages. In addition to the 2010 Olympics, Vancouver’s proximity to West Coast and Asian markets provides a number of future opportunities. The development of a highly ambitious California development program and vision for a Pacific Coast Hydrogen Corridor and the development of a Pacific Gateway Strategy for Canada will be strategic considerations for this cluster. In Central Canada, the proximity of hydrogen and fuel cells expertise in the Greater Toronto Area and Southern Ontario provides opportunities on at least two fronts. The Canadian automotive sector is highly concentrated in Southern Ontario and the automotive supply industry is well integrated into the North American automotive market. Secondly, recent indications that the Province of Ontario is prepared to pursue significant reinvestments in nuclear energy could provide new accessible sources of hydrogen. In Quebec, cluster opportunities lie primarily in the upstream production, transport, storage and distribution of hydrogen, particularly for stationary power applications.

Policy and Program Integration

Because of the wide ranging technical, marketing and policy issues associated with hydrogen and fuel cell development and distributed nature of Federal-Provincial and Inter-ministerial responsibilities, Canadian policy makers will be continually challenged to develop and implement coherent and effective policy and program measures that will ensure Canada’s future positioning. Despite significant efforts on the part of many stakeholders in this field to develop partnerships, networks and collaborations over the past decade the Canadian approach remains fragmented and the sector lacks critical mass in key areas of research and industrial capacity. In this vein, the role and mandate of such organizations as the Canadian Transportation Fuel Cell Alliance could be strengthened. For the fuel cell sector to emerge from the 2010 Olympics as a viable industry ready to compete internationally, industrial consolidation and program integration at all levels of government will need to occur.

Canada requires a holistic approach to commercialization. Mechanisms should not be independent of one another but should represent a logical, staged development approach where industry can transition from R&D to demonstrations to early deployments in an efficient manner. Without a coordinated approach, Canada risks losing focus and effectiveness of its past and future investments. Focus should be on enhancing R&D programs, working together with the US to build the North American hydrogen economy, and facilitating through fiscal policy introduction of products into the marketplace.

The difficulties of developing and sustaining technology intensive industries in Canada are not unique to the fuel cell sector but the policy implications of ensuring its success are both high risk and require bold actions. Policy leadership at all levels of government and in industry will be required.
Bibliography


Various Authors (2004) Canada’s Fuel Cell and Hydrogen Industry 04/05 Capabilities Guide

Appendix I – Technical Descriptions

Fuel Cell Technology:

The following is a non-technical explanation of how a PEM fuel cell works.

The Proton Exchange Membrane Fuel Cell (PEMFC)

The PEMFC operates at a relatively low temperature, which means it warms up quickly and does not require expensive containment structures. Platinum is typically used as a catalyst in this type of fuel cell. Constant improvements in engineering and material used in the PEMFC have increased the power density to a level where a device about the size of a small piece of luggage can power a car. Cyclibility adds to the advantages of PEMFCs. They are the leading fuel cell technology for use in transportation applications.

How a Fuel Cell Works

A fuel cell is a device that converts chemical energy into electrical energy. Hydrogen (which can be obtained from a variety of carbon-based fuels, including methanol, natural gas and petroleum or renewables), is combined with oxygen (obtained from the air) with a fuel cell to electrochemically produce electricity, water and heat.

The heart of the fuel cell generally consists of three primary parts: an anode, a cathode and an electrolyte. The electrical current flows from the cathode to the anode. The materials from which the fuel cell is composed determine the way in which the fuel cell produces electricity.

Cells

A basic Proton Exchange Membrane Fuel Cell (PEMFC) has hydrogen protons migrating from the anode through the electrolyte to the cathode. A platinum coating at the anode acts as a catalyst and helps to split the hydrogen molecules into positively charged protons and negatively charged electrons. The electrolyte membrane allows only the protons to pass through it to the cathode. The electrons cannot pass through this membrane and as a result, they flow (in the form of an electrical current) through an external circuit to get to the cathode, thus creating electricity. Oxygen supplied at the cathode then combines with the protons to form water.

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25 This profile has been taken from the Canadian Transportation Fuel Cell Alliance (http://www.nrcan.gc.ca/es/etb/ctfca).
Stacks

Individual fuel cells are typically combined into a fuel cell “stack”. The number of fuel cells in the stack determines the total voltage. The surface area of each cell determines the total current. Multiplying the voltage by the current yields the total electrical power generated, typically measured in kilowatts (kW).

Balance of Plant

Producing usable electrical power from a fuel cell requires more than just a fuel cell stack. In addition to the stack, a fuel cell system includes many components for functions such as: injecting fuel gases, managing a critical water balance, conditioning the power output and monitoring and controlling all the required system parameters (e.g., temperature and pressure). Without this supportive operating system, the fuel cell stack cannot produce usable power.
Hydrogen: 26

Properties

- Hydrogen is the most abundant element in the universe, accounting for 90 percent of the universe by weight. It is not commonly found in its pure form since it readily combines with other elements. It is found in the water that covers 70% of the Earth’s surface and in all organic matter.
- Hydrogen is a colorless, odorless, tasteless, and nonpoisonous gas under normal conditions on Earth.
- Hydrogen is highly flammable; it only takes a small amount of energy to ignite it and make it burn. It also has a wide flammability range, meaning it can burn when it makes up 4 to 74 percent of the air by volume.
- Hydrogen burns with a pale-blue, almost-invisible flame, making hydrogen fires difficult to see.
- The combustion of hydrogen produces no carbon dioxide (CO2), particulate, or sulfur emissions. It can produce nitrous oxide (NOX) emissions under some conditions.
- Hydrogen can be produced from renewable resources, such as by reforming ethanol (this process emits some carbon dioxide) and by the electrolysis of water (electrolysis is very expensive).
- Today, hydrogen is primarily used as a feedstock, intermediate chemical, or specialty chemical. Many envision a hydrogen future which will use hydrogen as an energy carrier or fuel.
- The energy in one gallon of gasoline is roughly equivalent to 1 kg of Hydrogen.
- Typically, a gasoline internal combustion engine (ICE) is 18-20% efficient; hydrogen ICEs are about 25% efficient; methanol fuel cells are about 38% efficient; and hydrogen fuel cell vehicles like Toyota’s FCHV-4 are 60% efficient—3 times better than today’s gasoline fuelled engines.
- The amount of energy produced by hydrogen per unit weight of fuel is about 3 times the amount of energy contained in an equal weight of gasoline, and almost 7 times that of coal.
- Hydrogen energy density per volume is quite low at standard temperature and pressure. Volumetric energy density can be increased by storing the hydrogen under increased pressure or storing it at extremely low temperatures as a liquid.

Production

The U.S. hydrogen industry currently produces 9 million tons of hydrogen per year (enough to power 20-30 million cars or 5-8 million homes) for use in the following processes:

- Chemicals production
- Petroleum refining

Metals treating
Electrical applications

Steam methane reforming accounts for 95% of the hydrogen produced in the U.S.

Other methods of hydrogen production include:
- Gasification of fossil fuels (e.g. coal)
- Splitting water using electricity (electrolysis), heat or light
- Thermal or biological conversion of biomass

Transportation
- Hydrogen is currently transported by pipeline or by road via cylinders, tube trailers, and cryogenic tankers, with a small amount shipped by rail or barge.
- Pipelines, which are owned by merchant hydrogen producers, are limited to a few areas in the U.S. where large hydrogen refineries and chemical plants are concentrated, such as Indiana, California, Texas, and Louisiana.
- Hydrogen distribution via high-pressure cylinders and tube trailers has a range of 100-200 miles from the production facility. For longer distances of up to 1,000 miles, hydrogen is usually transported as a liquid in super-insulated, cryogenic, over-the-road tankers, railcars, or barges, and then vaporized for use at the customer site.
- Hydrogen can be stored as a compressed gas or liquid, or in a chemical compound.