Discussion paper

Hydrogen Systems:

A Canadian Strategy for Greenhouse Gas Reduction and Economic Growth

A Canadian strategy for environmental protection and economic growth through the deployment of hydrogen technologies, systems and infrastructures

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Canada’s Hydrogen Strategy at a Glance

The energy services we enjoy today are not sustainable. First, the oil resources that underpin so many of these services, such as transportation, are being rapidly depleted. Second, the emissions that these services produce are creating an unacceptable build-up of greenhouse gases in the global atmosphere. If ignored, these trends may ultimately cause significant social, economic and political impacts around the world.

While we cannot prevent climate change from occurring, nor immediately eliminate our dependence on oil, there are ways to improve our prospects. We can:

- reduce our current emissions of carbon dioxide;
- diversify our energy base to reduce dependence on oil; and
- develop new energy systems with effectively zero life-cycle emissions.

This document sets out a Canadian mission and strategy for attaining these goals. In practical terms, it proposes that Canada should deploy sustainable energy systems and become a world leader in hydrogen technology by:

- developing hydrogen energy sources that are low in cost and have low life-cycle emissions, beginning with the existing hydrogen infrastructure and then expanding into a range of alternative sources;
- developing new energy service technologies such as low-emission hydrogen infrastructures for oil sands expansion, along with hydrogen transportation systems such as fuel cell vehicles; and
- preparing a market that expresses the value proposition for hydrogen and encourages stakeholders to support the hydrogen technologies that will help us meet our emission objectives.

The strategic plan recommends four major actions that will lead to the success of the mission:

1. **Government should establish national goals for climate change that will, in a global framework, stabilize the concentration of atmospheric CO_2.**
2. **Industry should build up the stakeholder base for hydrogen systems.**
3. **Industry and government should together develop a near-term, hydrogen commercialization plan that will position the Canadian energy industry at the forefront of the transition to the Hydrogen Age.**
4. **Government, industry and academia should together establish a long-term direction for the development of hydrogen systems.**

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Executive Summary

The Future of the Global Energy Supply

The continuing prosperity of our global society depends not only on access to affordable energy services, but also on making these services sustainable with respect to environmental consequences and future supply.

Energy systems based on oil are not sustainable. World oil resources are increasingly concentrated in the Persian Gulf states, and oil producers are expanding production to meet the new demands of growing Asian economies. These factors are raising concerns about supply security, and this in turn is causing oil prices to increase. At the same time, we are already observing the impacts of climate change, with increasing mean global temperatures resulting in reduced sea ice cover, glacier and permafrost melting, and changes in ecosystems. If we do not counter these trends, environmental disruption and escalating fears of oil shortages may seriously compromise the security of our global society.

Prospects for Change

Fortunately, there are ways to improve our prospects.

First, we must reduce the amount of carbon dioxide and other greenhouse gases (GHG) that our energy systems release into the environment.

Second, we must diversify our energy base to reduce our demand on oil resources, particularly with respect to transportation. While doing this, we must not only improve the efficiency of our energy systems and manage our carbon emissions effectively, but also adopt sustainable, non-fossil energy sources such as solar power, tidal power, wind power, hydro power and biomass**.**

Third, we must find ways to provide energy services that have effectively zero life-cycle emissions. *Hydrogen Systems: A Canadian Strategy for Greenhouse Gas Reduction and Economic Growth* proposes to achieve this by moving toward an energy system based on hydrogen and electricity, which can provide all the energy services our civilization needs and which can be generated from any energy source in ways that emit little or no carbon dioxide. This strategic change will provide us with a wider range of energy options, while the reduction in emissions will have many positive effects on the environment and human health.

Hydrogen and National Strength

Canada is well placed to lead the world in such a change. First, we have a mix of fossil and non-fossil energy sources almost unmatched among developed nations; these will play a vital role during the transition to a hydrogen-electricity future. Second, because of the creativity and initiative displayed by Canadian scientists, engineers, entrepreneurs and governments during the past 60 years, we are international leaders in many hydrogen technologies. Finally, Canadians in general have a well-founded optimism about the future and a well-grounded concern for environmental issues. This is reflected in a political leadership that will act on these concerns and will rise to the challenge of moving to a sustainable energy society.

Mission and Strategy

Hydrogen Systems: A Canadian Strategy for Greenhouse Gas Reduction and Economic Growth (hereafter referred to as *Hydrogen Systems*) sets out a mission and a strategic plan that directly address climate change and the depletion of world oil resources.

The mission is:

> **To deploy sustainable hydrogen energy systems such that, by 2025, Canada will no longer need to expand its use of fossil fuels for Canadian energy services. Building on its energy resource base and its leading expertise in hydrogen technologies Canada will become one of the world leaders in hydrogen technology development, deployment and the export of hydrogen service technologies.**

As well as establishing this mission, *Hydrogen Systems* outlines the basic strategies needed to develop hydrogen systems in Canada, using Canadian energy sources and technologies. These strategies were developed by the stakeholder group, which included representatives from government and academia, and from the hydrogen and energy industries. Through various forums, these stakeholders identified the barriers, enablers and key actions needed to achieve the plan's mission.

The strategy, as set out in *Hydrogen Systems*, has three segments:

- energy sources;
- the development of hydrogen energy service technologies; and
- development of the market and stakeholder base.

Energy Sources

The first segment of the hydrogen strategy addresses the energy sources. Our primary need is for hydrogen energy sources that are low in cost and that have low life-cycle emissions. Analysis indicates that the current hydrogen infrastructure, which is based predominantly on steam methane reforming (SMR) of natural gas, will produce marginal life-cycle emission benefits, especially when compared with the improvements in incumbent technologies expected during the next 10 years. Alternative hydrogen production processes are needed to achieve potential emission reductions; among these are processes based on fossil fuel reforming with carbon dioxide capture and sequestration, and electricity generated by energy sources with low greenhouse gas (GHG) emissions.

Hydrogen, like electricity, is expensive to transport over long distances. Hydrogen systems in Canada, therefore, are likely to develop around regionally available energy sources. Some possible examples are the renewable resources in Manitoba, Quebec and the coastal provinces; renewable and nuclear resources in Ontario; and, in Alberta and Saskatchewan, renewable resources and fossil fuels with carbon capture and sequestration. In the initial stages of market development, the hydrogen supply might either “piggyback” on existing industrial hydrogen infrastructure or come from on-site production.

Developing Energy Service Technologies

Hydrogen energy service technologies comprise the second segment of the hydrogen strategy. In this area, the development of the oil sands might provide an opportunity for establishing low-emission hydrogen infrastructures, since these can serve the near-term needs of heavy oil upgrading.

Another major opportunity for infrastructure development will arise as hydrogen vehicles penetrate consumer markets, stimulating a high demand for hydrogen. However, achieving a shift to hydrogen-powered vehicles will require strong transition strategies, since many of the ideal, low-emission hydrogen pathways are still relatively immature. The broad commercialization of fuel cells is likely 10 years away, and on-board hydrogen storage remains a challenge. Nevertheless, feasible transition strategies can be built in the near term around pathways such as hydrogen internal combustion engines (ICEs) and fuel cell vehicles designed for high-value, niche applications such as public transport.

Preparing Markets and Stakeholders

The third segment of the strategy addresses the preparation of a market that expresses the value proposition for hydrogen. The single greatest barrier to this is the design of the existing energy market, which places no value on environmental factors — in particular, on the value of avoiding CO_2 emissions.

Stakeholder analysis also indicates that general market acceptance for hydrogen systems is not yet at the "tipping point." Stakeholders, in the broad sense, do support meeting the necessary emission objectives and are in favour of developing the technologies that will achieve this. However, they are uncertain as to whether hydrogen technologies are a practical and economic solution, and are concerned about the time-to-market of these technologies.

Recommendations of the *Hydrogen Systems* Strategic Plan

The recommendations of the strategic plan can be summarized as follows:

1. **Government action is needed to establish national goals for climate change that will, in a global framework, stabilize the concentration of atmospheric CO_2. This is estimated to require a 60 to 80 percent reduction in Canadian per-capita CO_2 emissions by 2050, and a 95 percent reduction by 2150.**

2. **Industry needs to build up the stakeholder base for hydrogen systems. In the near term, this should focus on bringing the energy industry as a whole to this conclusion.**

3. **Industry and government need to work together to develop a near-term commercialization plan. This plan must help position the Canadian energy industry at the forefront of the transition to the Hydrogen Age. It should set a goal of using hydrogen systems to achieve a minimum 1 Mt reduction in CO_2 emissions by 2012.**

4. **Government and industry, working with academia, need to establish a long-term direction for the development of hydrogen systems in terms of advancing technology and public education.**

Hydrogen Systems: A Canadian Strategy for Economic Growth and Greenhouse Gas Reduction **sets out a plan that proposes nothing less than moving our country's energy system into the Hydrogen Age.**

1.0 The Global Mission to Reduce Greenhouse Gas Emissions.

1.1 Climate Change and the Future.

Climate change is starting to influence the social, political and economic systems of the world. This climate change is being driven by the warming of the earth, which in turn is caused by rising levels of greenhouse gases (GHG) in the atmosphere.

Greenhouse gases occur naturally and are part of a complex gaseous exchange of gigatonnes (Gt) of CO_2 per year, involving the natural balance among sources such as animals, forest fires and organic decomposition, and sinks such as soils, vegetation, the ocean and the atmosphere.[1]

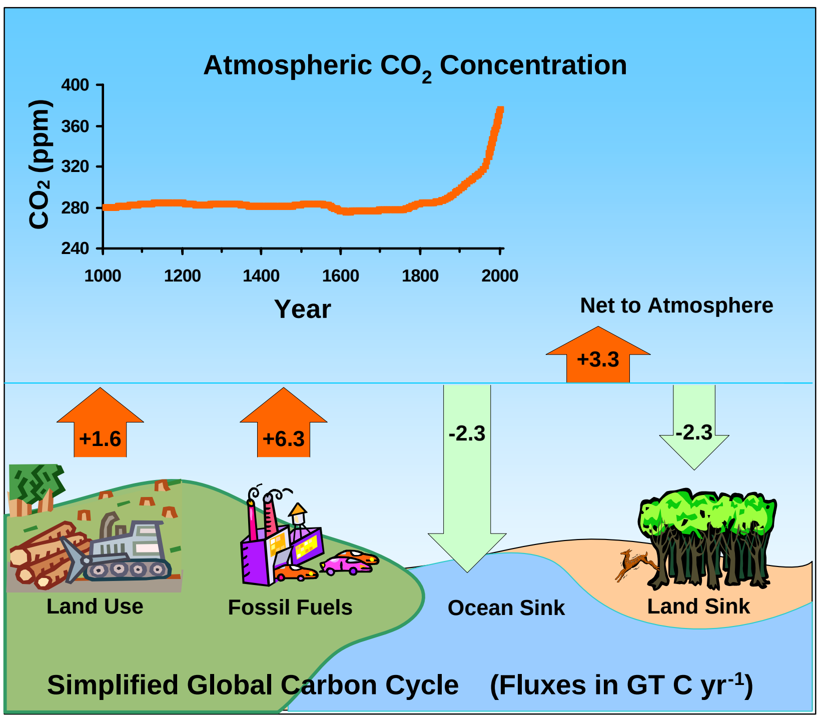


Figure 1[2] - Simplified Global Carbon Cycle (lower) and Atmospheric CO_2 Concentration[3] (upper).

The earth's present warming trend is due largely to a GHG imbalance created by anthropogenic sources. This GHG is produced primarily through the burning of fossil fuels, and during the past 200 years it has accumulated so that its concentration in the atmosphere has risen by 31 percent (see Figure 1).

The present atmospheric concentration of CO_2 — approximately 375 ppm — is higher than at any time during the last 400 000 years.[4]

As a result of this increase, the mean global temperature is projected to rise by 1.4°C to 5.8°C by the year 2100.[5] This should be compared to a 0.6ºC warming of the mean surface temperature during the past century. While debate continues about the pace of the change and the magnitude of its impact, there is scientific consensus that global warming is indeed changing the world's climate, and that this will affect most human activities.

These changes have been examined in Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC).[6] With respect to rises in sea level, for example, the TAR states that, during the next century:

> Many coastal areas will experience increased levels of flooding, accelerated erosion, loss of wetlands and mangroves, and seawater intrusion into freshwater sources as a result of climate change. The extent and severity of storm impacts, including storm-surge floods and shore erosion, will increase as a result of climate change including sea-level rise.[7]

Such changes will affect human health. Again according to the TAR,

> … any increase in flooding will increase the risk of drowning, diarrhoeal and respiratory diseases, and, in developing countries, hunger and malnutrition. If cyclones were to increase regionally, devastating impacts would often occur, particularly in densely settled populations with inadequate resources. A reduction in crop yields and food production because of climate change in some regions, particularly in the tropics, will predispose food-insecure populations to malnutrition, leading to impaired child development and decreased adult activity.[8]

These are two examples of the environmental, economic and social problems with which humanity may have to cope. They are not the only ones; the TAR describes many other potential difficulties, some of which are very severe.

Reducing the future impacts of climate change will require major reductions in worldwide per-capita GHG emissions within the next 50 years. The Kyoto Protocol proposed an international framework to achieve these emission targets. However, the Kyoto targets are only the first steps toward stabilizing atmospheric CO_2 concentration.

An attainable target for a stabilized concentration is currently considered to be approximately 550 ppm, or about twice pre-industrial levels.[9] To reach this target, however, global CO_2 emissions must be reduced far more aggressively than Kyoto demands. The mitigation strategy depicted in the IPCC's Wigley, Richels and Edmonds (WRE) 550 scenario[10] (see Figure 2) proposes a challenging but realistic course of action that would result in a global mean temperature rise of 2.5°–3.5°C. It should be acknowledged, however, that enormous costs would be associated with these mitigation actions.

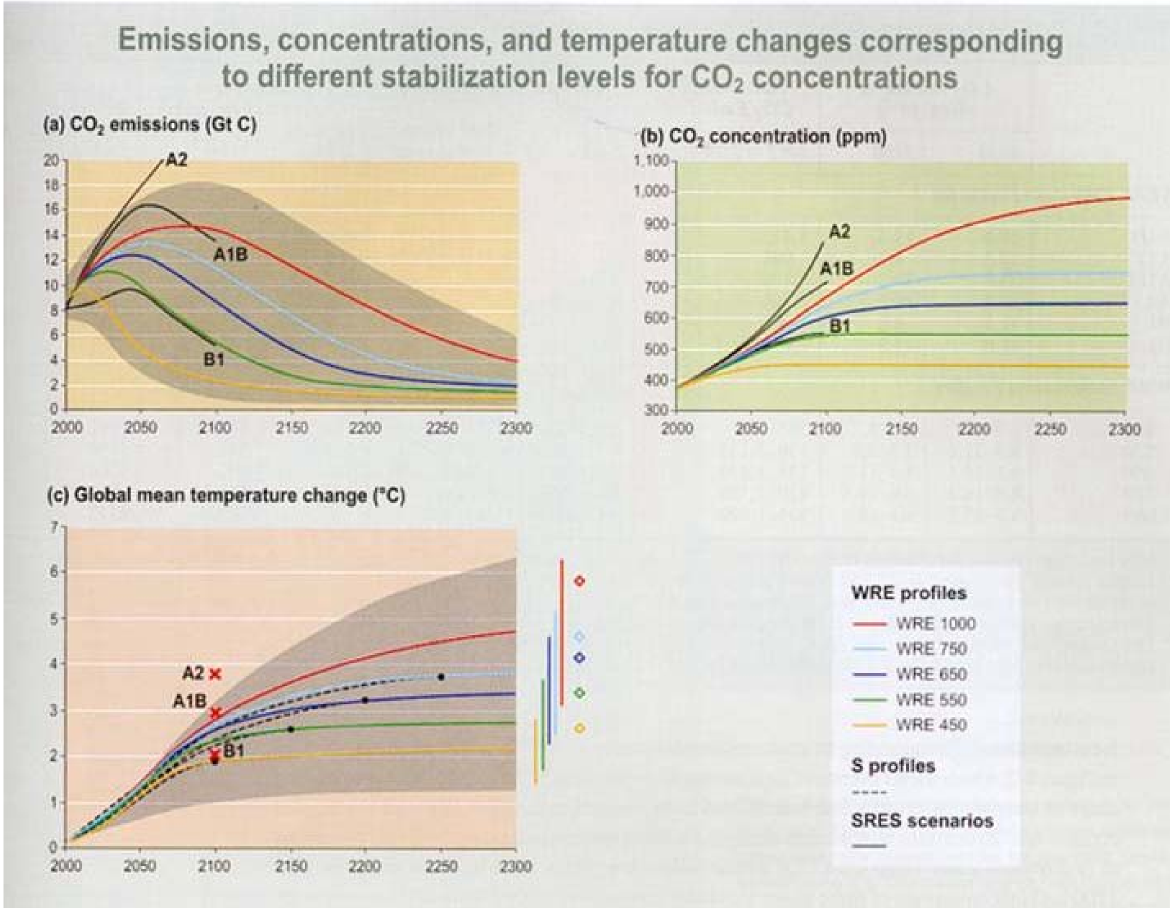


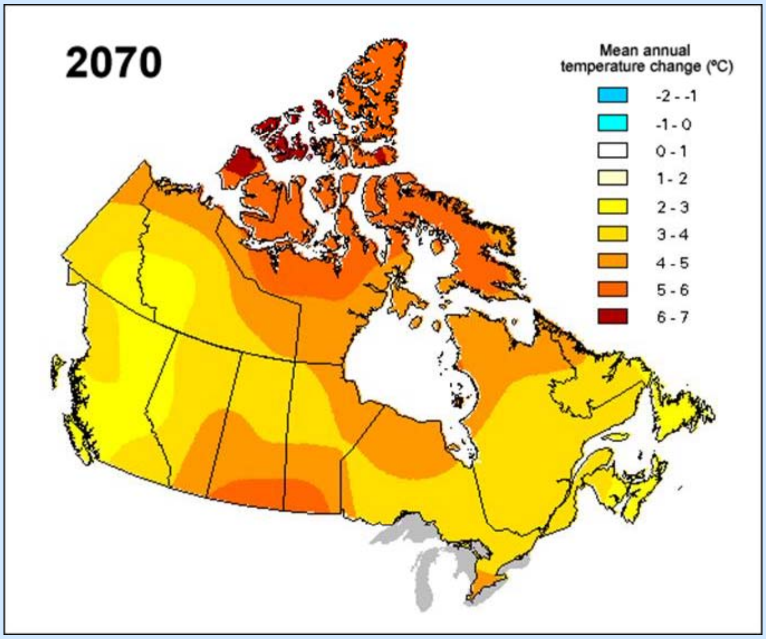
Figure 2 - WRE Emission Models Used to Predict Climate Change.[11]

Following the WRE 550 profile represented in Figure 2, global emissions would peak at around 40 Gt of CO_2 per year (11 Gt of carbon) in 2030, drop below 1990 levels by 2075 and eventually stabilize by 2200 at less than 7.3 Gt of CO_2 per year (2 Gt of carbon), which is roughly 20 percent of today's global emissions.

Comparing this profile with global emission projections, according to the "business as usual" (BAU) scenario, and based on historical rates of emission increase, achieving the 2050 emission objective of 36 Gt per year of CO_2 in 2050 would amount to a 50 percent reduction in global emissions.[12] If world equal-per-capita emission allocations were applied to achieve these emission targets, Canadians would have to lower their annual emissions from today's level of 24 t of CO_2 per capita to 4 t per capita, or by approximately 80 percent.[13] By 2150, their annual emissions would need to drop to 1 t per capita, a reduction of over 95 percent from current levels.[14]

Impact on Canada

During the next 100 years, assuming a moderate emissions scenario, annual average temperatures in Canada's northwest are projected to rise by 3–5ºC over land and by up to 7ºC over the ocean. In the same region, winter temperatures are projected to increase by 4–7ºC over land and by 7–10ºC over the ocean.[15,16]



A number of countries and some of the world's largest energy companies[17] are beginning to advocate global action towards establishing longer-term post-Kyoto emission limits. In the United Kingdom, for example, Prime Minister Blair renewed his commitment to a global process to reduce CO_2 beyond Kyoto targets. He has promised to make it a priority of the G8 during his term as chair, and highlighted the recent conclusion of the Royal Commission on Environmental Pollution, which was that the U.K. should commit itself to reducing carbon dioxide emissions by 60 percent by 2050.[18] This would cut the United Kingdom's per-capita-per-year emissions, which are currently half that of Canada's, from 10 t per capita to 4 t per capita, in line with equal-per-capita emission targets associated with the WRE 550 scenario.

As the discussion and planning for climate change begins to look beyond Kyoto, we must also recognize the second emerging threat to our long-term security. The world is rapidly arriving at the peak in conventional oil supplies, and oil resource depletion will become an increasingly important energy price and security driver.

Depletion of Conventional Oil Reserves

Reducing oil consumption becomes even more crucial in light of the rapid depletion of the world's conventional oil resources. Proven oil reserves, estimated to be 1147 billion barrels, provide a 40-year supply at current consumption rates of 30 billion barrels per year.[19] Assuming current growth trajectories, oil demand is expected to double during this time, leading to tighter supplies and higher prices. Transportation is expected to play an increasingly dominant role in oil consumption, accounting for almost all the growth in oil demand in OECD countries during the period leading up to 2030.[20]

Oil reserves will also become increasing insecure as they become concentrated in certain geographical regions. The Middle East, with 63 percent of today's proven reserves, is expected to see its share of these reserves increase as smaller oil fields in other regions are depleted.

1.2 Transforming Canada's Energy Systems: Kyoto and Beyond.

A breakdown of GHG emissions according to the sectors in the Canadian economy (Figure 3) shows that the only way to achieve the necessary reductions is through "decarbonizing" the energy system, primarily by reducing the burning of fossil fuels.

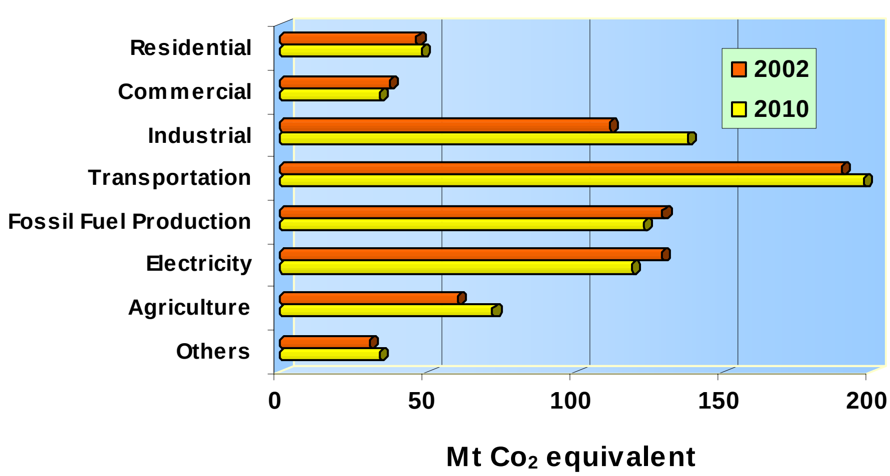


Figure 3 - CO_2 Emissions in Canadian Economy by Sector.[21]

National Climate Change Goal[22]

"to become the most sophisticated and efficient consumers and producers of energy in the world and leaders in the development of new, cleaner technologies."

The Government of Canada's *Climate Change Plan for Canada*[22] involves both adaptation and mitigation that will, through international cooperation under the Kyoto Protocol, reduce global CO_2 emissions. In establishing its targets according to the Kyoto framework, however, Canada has taken on a daunting challenge. Not only do we have the third-highest per-capita emissions in the world, our energy consumption currently stands at 8.6 EJ/y and is expected to rise to 11.5 EJ/y by 2030.[23] As a result, there remains a large gap between our emission objectives and our actual emission rate (see Figure 4). Under Kyoto, by 2012 we should expect to reduce our emissions to 571 Mt-equivalents of CO_2 per year. However if our emissions continue to follow the current business-as-usual (BAU) trajectory, they will grow to 809 Mt-equivalents of CO_2 per year — a yearly shortfall of 238 Mt. Moreover, as the population grows, the shortfall will increase into the indefinite future.

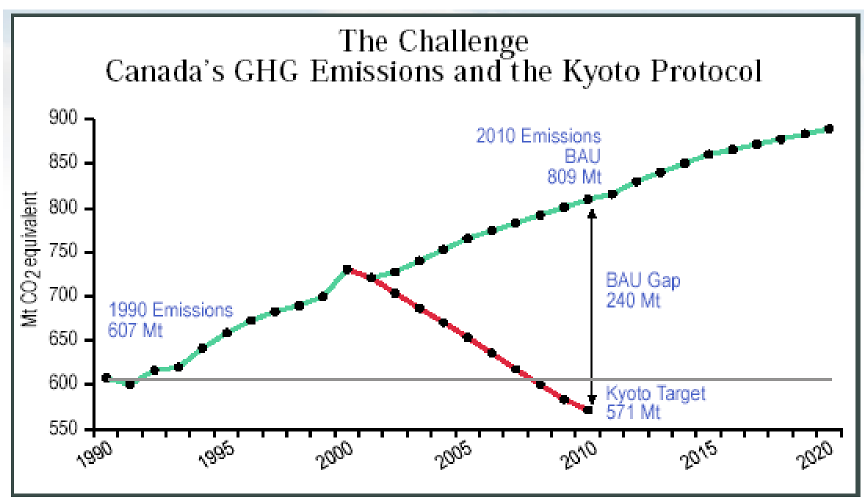


Figure 4 - The BAU Gap.[24]

However, Kyoto is only the first step. Much deeper cuts will be necessary during the years between 2012 and 2050. Depending on negotiations in future climate change treaties, Canada's obligation could require a reduction in per-capita GHG emissions of 60 percent or more over the BAU trajectories. To achieve these objectives, a radical redesign of energy systems will be required to convert current GHG-emitting energy sources to sources that are effectively carbon-neutral.

The mission proposed by the Hydrogen Strategic Plan Working Group sets a reasonable goal that is near the midpoint of this time line.

The Mission:

> **To deploy sustainable hydrogen energy systems such that, by 2025, Canada will no longer need to expand its use of fossil fuels for Canadian energy services. Building on its energy resource base and its leading expertise in hydrogen technologies Canada will become one of the world leaders in hydrogen technology development, deployment and the export of hydrogen service technologies.**

But do hydrogen-based energy systems really offer an answer to our intertwined problems of energy resource depletion, global warming and climate change? The following pages explore this proposition, along with the strategies and key actions that are required if Canada is to become a leader in the use of hydrogen systems to achieve greenhouse gas reductions.

2.0 Why Hydrogen Systems Are Needed.

2.1 Hydrogen as an Energy Currency.

What is important to society is not energy in itself, but the services that energy provides, such as heating, transportation and manufacturing. Consequently, it is useful to see hydrogen not just as an energy carrier, but also as an energy "currency" within an energy system chain. As an energy currency, it forms the central link between energy sources and the services that society needs (see Figure 5).

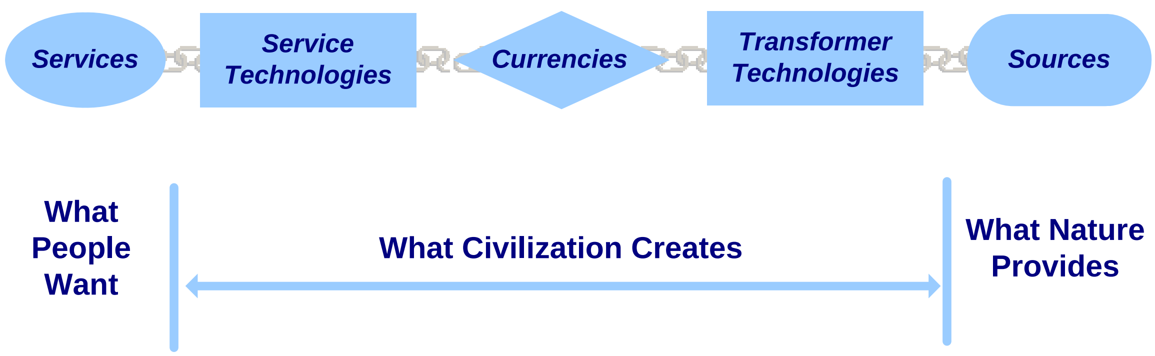


Figure 5 - The Energy System Chain.[25]

Hydrogen as an Energy Currency.[26]

The role of hydrogen and electricity as energy currencies, with respect to functional constraints, is analogous to that of monetary currencies:

- Monetary currencies, such as dollars or yen, enable financial transactions but are not, in themselves, sources of wealth. Similarly, energy currencies enable energy transactions but are not, in themselves, sources of energy.
- No single currency can be used for all transactions. Each financial currency, be it dollars or yen, functions only within a certain range of transactions. In a similar way, each energy currency can only be used for a range of transactions. For example, electricity can't power airplanes and kerosene can't run computers.

- In both cases, the efficiency of inter-currency conversion is always less than 100 percent. When converting euros to dollars, for example, we pay a monetary price. When converting gasoline to electricity, we pay an energy price.

- In both cases, currency exchange is usually more difficult in one direction than in the other (it's easier to convert U.S. dollar to Zambian kwacha than the other way around). In the case of energy, diesel fuel can readily be converted into electricity, but no one tries to do the reverse.

- During the last century, there has been a progressive decoupling of the material of the currency from the material of the currency's source. This has brought profound systemic liberty. The material of firewood, for example, means that its source must be trees. The material of gasoline and diesel means they must come from fossil sources. But the "material" of electricity — electrons — is completely decoupled from the material of the source used to manufacture it. Better yet, the "materials" of *both* hydrogen and electricity are completely decoupled from the materials of their energy sources, which means that *any* energy source may be used to manufacture both the hydrogen currency and the electricity currency.

From a practical standpoint, one of the chief advantages of hydrogen is that it can be readily converted into electricity, and vice versa. This means that an energy system based on both hydrogen and electricity can be extremely adaptable. For example, while electricity cannot be stored in widely useful ways or in substantial amounts, the energy it contains can be converted into hydrogen, which *is* storable. Similarly, while electricity is not a material feedstock, converting it to hydrogen makes it into one. Reversing the process, stored hydrogen can be changed into electricity as and where it is needed.

Because using hydrogen energy services results in no harmful emissions at the point of use, its life-cycle emissions, like those of electricity, depend on the nature of the energy source used to generate the hydrogen. In this way, transforming fossil fuel energy to hydrogen and electricity, and capturing the emissions during the energy transformation process, could be used to manage emissions from fossil fuel energy sources. In many applications, especially transportation, it is easier to capture the emission at the transformation step rather than the point of use.

The depth and diversity of hydrogen's resource base, along with its potential for emission-free energy generation, shows great promise for a global system of sustainable energy development, in which our present fossil-based energy services would be transformed into a new system based on hydrogen and electricity. Such a transformation would allow us to meet our existing social and economic needs without compromising the ability of future generations to meet their own.

2.2 Global Action on the Need for Hydrogen Systems.

It is widely recognized that we must reduce global GHG emissions in order to mitigate the effects of climate change. It is also becoming clear that hydrogen, when produced from clean and sustainable sources, can play a central role in solving the pollution and depletion problems associated with fossil fuels.

As a result, governments around the world have increased their support for the development of hydrogen technology and hydrogen energy systems. In April 2003, for example, the United States, Canada and thirteen other nations established the International Partnership for the Hydrogen Economy (IPHE) to coordinate hydrogen research, development and technology. The IPHE's goal is to create a framework for international co-operation on the development of hydrogen and fuel cell technologies, and to provide a forum for codes and standards that can accelerate the cost-effective transition to a global hydrogen economy.[27]

The United States has undertaken several major initiatives to develop hydrogen technologies. In 2002, it published its National Hydrogen Energy Roadmap, setting out a long-term strategy for the research and development of hydrogen energy systems. The U.S. Department of Energy has also developed its Hydrogen, Fuel Cells and Infrastructure Technologies Program to coordinate the development of hydrogen technologies and applications.[28] In 2003, the White House proposed the FreedomCAR program, focusing on hydrogen fuel cell vehicles.[29] Also announced was President Bush's Hydrogen Fuel Initiative or FreedomFUEL program, which deals with research and development into hydrogen production, delivery and storage.[30]

An earlier, global hydrogen initiative belongs to the International Energy Agency (IEA), which was founded in 1974 after the first oil crisis.[31] This IEA initiative is the Hydrogen Implementing Agreement (sometimes called the IEA Hydrogen Agreement). Its purpose is to advance hydrogen technologies and accelerate hydrogen's acceptance and widespread utilization.

In April 2003, the IEA also set up the Hydrogen Co-ordination Group (HCG), with four tasks: to develop a comparative review of national programs, review the activities of the Implementing Agreement, recommend further collaboration and identify analyses to guide IEA work. Canada is a member of the HCG, as are 24 other countries including those of the European Union.[32]

Europe has been active on a broad scale; in 2002, the European Commission announced 2.1 billion euros (about CAN$3.3 billion) for research into renewable energy, largely in hydrogen technologies.[33] Within Europe, Germany is developing a new hydrogen vision that was to be completed by the end of 2004. The strategy includes hydrogen production from fossil fuels with CO_2 sequestration, concentration on major types of fuel cells, development of fuel cell materials and components, and work on codes and standards.

Japan is committing itself to hydrogen on a large scale. By 2010, it hopes to have 50 000 fuel cell vehicles (FCVs) in use and, by 2020, it intends to increase the number to 5 million.[34] It has well-developed plans for hydrogen commercialization, including the construction of a fuelling infrastructure for the intended numbers of FCVs. Japanese R&D, like that of other countries, includes PEM fuel cell (FC) systems, molten carbonate FCs, solid oxide FCs, micro FCs and lithium ion batteries for FC vehicles.

Iceland, which has vast hydraulic and geothermal resources, has the potential for producing inexpensive electricity. Through strong government action, it has become a living laboratory for the Hydrogen Age. With Shell, Norsk Hydro and DaimlerChrysler as partners, the country intends to position itself as a centre for international research and development into hydrogen technology and use.[35]

In summary, the global community is clearly committed to a future in which hydrogen-based energy systems are the norm rather than the exception. Canada is already among the world's leaders in this undertaking. But if we are to maintain this position and take full advantage of the opportunities of the Hydrogen Age, we must create a well-crafted strategy for doing so. And once the strategy exists, we must take concerted and determined action to carry it out.

3.0 Why Now: Canada as a Global Leader in the Hydrogen Age

Canada has abundant, low-cost energy resources, which have many obvious advantages for our economy and society. However, our inexpensive energy provides little incentive for conservation. As a result, we have paid insufficient attention to the actual value of energy, and rank first among the world's wealthiest nations with regard to per capita energy consumption — over 30 percent higher than the US, and twice that of major European nations.[36] We are therefore large producers of greenhouse gases, and our energy inefficiencies take a hidden toll on our economy.

Nevertheless, Canada is well positioned to benefit economically, technologically and scientifically if the world vigorously pursues the development of a hydrogen economy. We are leaders in hydrogen system technologies and are also one of the world's largest per-capita producers of hydrogen,[37] about half of which is produced by our oil and gas industries. Combining our technical expertise in hydrogen production with reductions in hydrogen-production emissions within the oil and gas industry could position Canada as a leader in the Hydrogen Age and could result in significant reductions in Canada's CO_2 emissions before the end of the first Kyoto Accord commitment period.

We are also at the forefront of fuel cell and other hydrogen technologies, and have the means to maintain this role because of innovative Canadian companies such as Ballard Power Systems, Stuart Energy Systems, Dynetek and Hydrogenics. The governments of British Columbia, Manitoba, Alberta and Quebec have also recognized the potential of the hydrogen economy and are making hydrogen a part of their energy system and industrial development strategies.

A successful hydrogen economy will depend on the widespread availability of environmentally friendly and competitively priced hydrogen. Without this, hydrogen energy service technologies will have little chance of competing with existing, fossil-fuelled energy systems. Canadians, however, are beginning to understand the climate change problem and want to find ways to deal with it.[38] They are becoming aware that we can use energy much more wisely, and that new energy technologies for improving efficiency and lowering carbon emissions are needed to moderate the effects of climate change. This growing public support, coupled with our abundant energy resources and our technological expertise, makes Canada a natural leader for the transition into the Hydrogen Age.

3.1 A Resource Base for the Hydrogen Age.

Canada has a vast quantity and range of energy resources, all of which can be used to produce hydrogen. Although the country has only 0.5 percent of the global population, it holds about 5 percent of the planet's proven reserves. When coal is excluded, Canada's energy inventory actually doubles to 10 percent of the world's proven reserves. (An inventory of Canada's resource base compared with world figures appears in Appendix B.)

Canada is the world's largest producer of hydroelectric power[39] and possesses an abundance of coal, natural gas and uranium. It has the second-largest proven oil reserves in the world after Saudi Arabia, with recoverable reserves exceeding 175 billion barrels.[40]

This wealth of resources and technology could serve as the foundation for the production of low-cost, clean hydrogen. Although producing hydrogen from fossil fuels generates GHG, Canada also has substantial capacity for carbon sequestration, and is developing capabilities in this area.

Non-conventional energy resources, such as coal-bed methane, could also add significantly to Canada's diverse energy stockpile. Renewable energy from wind, solar and biomass will play a growing and important role, but are difficult to quantify fully at present.[41]

Canada's wealth of resources and technology also gives us a responsibility for showing leadership in finding low-carbon solutions to the world's energy needs. If we vigorously pursue a commitment to the Hydrogen Age and to mitigating climate change, we will position Canada as a leader in the global shift towards clean energy systems. At the same time, maintaining our lead in the face of growing international competition demands that we focus on the mobilization of our resources and on partnerships among governments, industry, academia, and research organizations. This is a key part of the vision for Canada's entry into the Hydrogen Age.

4.0 A Vision for Canada's Hydrogen Future.

In a broad perspective, hydrogen energy systems can be scalable, clean, quiet and efficient, and can provide an even wider array of conveniences than we now enjoy. To a large extent, hydrogen systems could be deployed on a distributed rather than a centralized basis, which implies that power sources and hydrogen-based energy conversion systems could be located close to their users, making the energy systems more flexible and adaptable than is now possible. [42]

While some of the existing infrastructure can be used and adapted, new infrastructure elements will also be needed. As a result, the hydrogen energy systems of the future will likely be quite different from the fossil-based systems we see around us today.

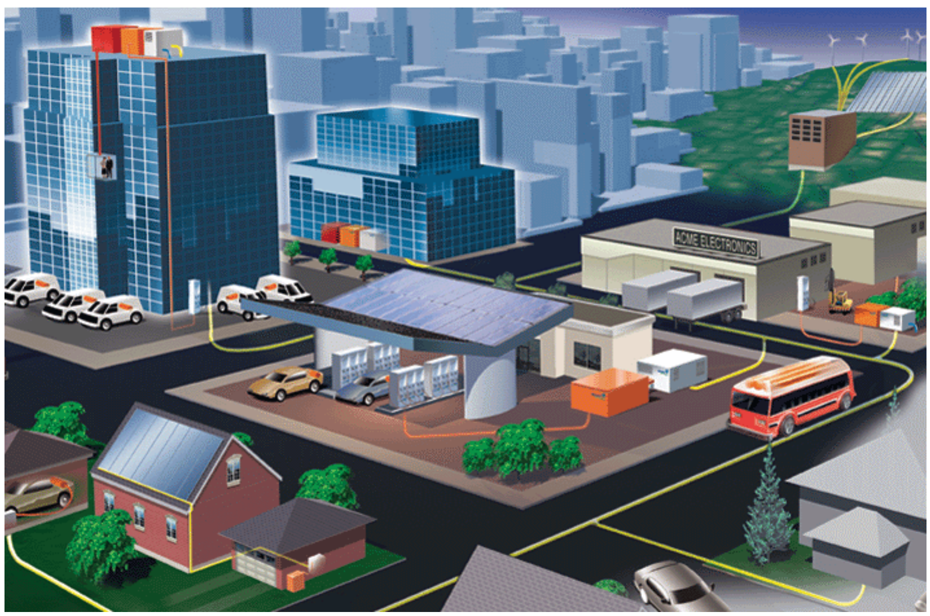


Figure 6 - Vision of Hydrogen-Electricity Economy (courtesy of Stuart Energy Systems).

The vision of Canada in this future Hydrogen Age provides some very desirable benefits. Among them are:

- mitigation of climate change, reducing environmental instabilities;
- reduction of air pollutants such as particulate matter, NO_x, SO_x and CO, all of which affect human health and reduce agricultural yields;
- an increased use of indigenous energy and diminished global dependence on oil, resulting in a reduction of the political, economic and social instabilities produced by this dependence;

- the establishment of a dependable, efficient and clean energy system that can readily use renewable resources;
- the development of new energy services, stimulating Canada's economic development and technological progress;
- opportunities for Canada to export both its hydrogen technologies and its energy in the form of value-added energy carriers (hydrogen and electricity);
- increased use of decentralized, local resources to supply domestic energy needs, resulting in increased control over energy systems and improved efficiency, reliability and social effects; and
- sustainable development, in which:
  - human industrial and economic activities do not deplete non-renewable energy resources or limit the ability of future generations to meet their own needs; and
  - human industrial and economic activities do not degrade the environment, but instead sustain a high quality of life and social equity throughout the world.

By following this vision of a hydrogen future, Canada would contribute in a very important way to the development of healthy, secure and prosperous communities both at home and abroad.

4.1 Implementing a Vision of Global Leadership in the Hydrogen Age: What Could Be.

In the near term, by 2012, Canada could stake its claim as a global hydrogen leader by being the first country to use hydrogen technologies to reduce annual CO_2 emissions by 1 Mt from current levels. Canada could also lead the world on a per-capita basis in deploying hydrogen technology, including the highest per-capita use of commercial vehicles and personal automobiles powered by fuel cells or hydrogen ICEs.

Other near-term possibilities are to develop entry markets for portable hydrogen-fuelled power applications, and to have the highest installed per-capita base of stationary, hydrogen-fuelled products. Canadian industrial processors, such as oil and gas producers, could build hydrogen infrastructures that would use CO_2 sequestration and non-fossil hydrogen production to achieve substantial reductions in carbon emissions. Canada could lead the world in development and implementation of CO_2 sequestration technology.

In the mid-term, by 2025, Canada could create viable markets for sustainable hydrogen energy systems, which would by then be fully commercial and widely deployed. The country could be a leader in supplying hydrogen technologies, systems and infrastructures designed to deliver improved energy services and reduced GHG emissions. Hydrogen systems, using Canadian technologies such as fuel cells, electrolysers, hydrogen storage and hydrogen sensing and control devices, could be exported around the world. Canada would no longer need to expand its use of fossil fuels for energy services, although it would continue to develop its fossil fuel energy sources.

In the distant future, by around 2075, Canada could become the world's largest exporter of energy currencies and energy technologies. By this time, hydrogen and electricity would be evolving into the dominant energy carriers, replacing fossil fuel energy services in the form of natural gas, gasoline and diesel.

This is a bold vision that will require commitment, stamina and wisdom to implement. But we have only recently set out along this road. How far, exactly, have we come, and what is the state of hydrogen technology today? What are its prospects?

5.0 Hydrogen Systems Today

Hydrogen is a major chemical feedstock in Canada, supporting a host of economically essential processes for materials refining and production. Yet it plays almost no role as an energy carrier in Canada's energy services, because the technologies that will usher in the Hydrogen Age are not yet commercially ready. Some are still under development and others cannot compete with the incumbent technologies. The reasons for this will become more apparent as we examine Canada's hydrogen infrastructure, the state of our hydrogen technology and the design of today's energy marketplace.

5.1 Canada's Current Hydrogen Infrastructure.

5.1.1 Hydrogen Production.

Canada produces nearly 3 million tonnes of hydrogen per year.[43] This is about one-third of the U.S. hydrogen production rate and makes Canada the largest per-capita hydrogen producer in the OECD.[44]

The vast majority of this hydrogen is directed to captive use in the chemical industry (see Figure 7): 34 percent of it goes to chemical production, 27 percent to heavy oil upgrading and 23 percent to refining; the remaining 16 percent is chemical-process by-product. Producers and users trade a proportion of it, but a mere 0.6 percent is produced and sold as "merchant hydrogen" (gas that is sold in small quantities and delivered to the customer's site).[45]

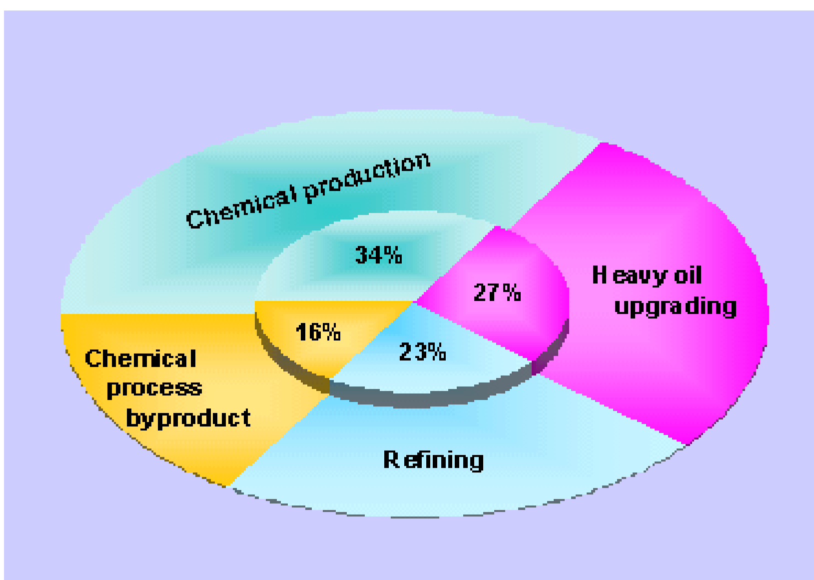


Figure 7 - Hydrogen Use in Canada's Chemical Industry[46].

Most of the hydrogen used in the chemical sector is produced from natural gas by the steam methane reforming (SMR), while the refining industry produces hydrogen by reforming more complex hydrocarbons available within the refining processes. Electrolytic hydrogen production makes up an estimated 5 percent of Canada's supply.[47]

Because of its large fossil-fuel resources, the Western Region dominates Canadian hydrogen production, and Canada's largest hydrogen plants are located in its oil-upgrading facilities. Four plants in Alberta together produce 770 000 t of hydrogen annually.[48] The upgrading of heavy oil from the Alberta oil sands is Canada's fastest-growing hydrogen demand sector, with annual production expected to rise to 2.8 Mt per year by 2020.[49]

Canada's 16 oil refineries have hydrogen production capacities ranging from 5,000 to 125 000 t annually. By comparison, the by-product hydrogen generation capacity of the 17 salt electrolysis plants lies at the lower end of this scale, producing from 5,000 to 14 000 t per year per plant.[50]

Hydrogen produced by a large natural gas reformer can compete with gasoline on an energy-cost basis, provided that there are natural gas wells near the production facility. Under these conditions, if natural gas costs are approximately US$3.50 per gigajoule (GJ), hydrogen production costs can be in the range of about US$0.75 per kilogram or on an energy basis[51] about US$0.20 per litre of gasoline-equivalent. However, this competitiveness may not last; the depletion of conventional natural gas supplies in the Western Sedimentary Basin, coupled with the expansion of Canada's oil sands, is already leading to steep increases in the costs of natural gas and of the hydrogen produced from it. With future contracts for natural gas lying in the range of US$7.00 per GJ, hydrogen production costs would increase to around US$1.35 per kilogram.[52]

Another problem with hydrogen production from natural gas is its significant level of GHG emissions, with current SMR processes generating about 12 t of CO_2 per tonne of hydrogen produced.[53] While the high purity of reformer-generated CO_2 suits it for sale as an industrial gas, only minor quantities are collected and sold, because at present there are only limited markets for CO_2.

5.1.2 Hydrogen Distribution and Delivery.

Although cost-competitive with gasoline on an energy basis, captive hydrogen generated on-site in an integrated chemical plant (sometimes referred to as "inside" or "over-the-fence" hydrogen) is delivered as a low-pressure gas, which is in a relatively difficult form to handle. Its low volumetric energy density — less than one-third that of natural gas[54] — poses a challenge to its use as an energy carrier. To deliver it as a "packaged gas" to customers in merchant markets, its energy density must be increased by compression or liquefaction. Unfortunately, this exacts considerable economic and energy costs that can drive the price of delivered gas as high as CAD$50 per kilogram, based on its purity, quantity and the distance from the hydrogen source. This is more than 50 times the production cost of the largest hydrogen-producing plants.

Over short distances, merchant hydrogen is distributed by tube trailer or, for smaller quantities, in individual, high-pressure steel cylinders. Over longer distances, it is transported as a liquid in cryogenic tanks. To provide it in this form, Canada has hydrogen liquefaction facilities in Sarnia, Ontario; Magog, Quebec; and Bécancour, Quebec. Pipeline transport is possible as well, as in the case of the 52-km hydrogen pipeline that connects hydrogen producers and users in Northern Alberta. Even longer hydrogen pipelines exist in other parts of the world, including the 800-km pipeline in the Mississippi Valley and the 1,500-km pipeline in the Belgium/Holland/Germany region of Europe. This demonstrates that the technology, operating principles and costs of pipeline transport are well understood.[55]

Such an infrastructure is capable of supporting the technology development of hydrogen energy services, but commercialization will demand new infrastructures to reduce costs and life-cycle emissions. Some new infrastructures have already been demonstrated; these are based on distributed electrolysis and distributed SMR, but they have yet to meet the necessary cost and/or emission targets.

Figure 8 - Liquid Hydrogen Tanker (courtesy of Air Liquide Canada).

Figure 9 - Hydrogen Pipeline (courtesy of Air Liquide Canada).

Near-term actions will be determined by opportunities in the existing infrastructure, where hydrogen can be obtained cheaply from common processes and where there are production surpluses. Not all industries generate surpluses, however. The oil refinery sector uses virtually all the hydrogen it makes, as do the chemical industries that use hydrogen as a feedstock.

On the other hand, certain chemical processes generate hydrogen that is not directly useful to the generating facility. In some regions, particularly in Alberta, Ontario, Quebec and New Brunswick, complementary chemical industries have been constructed near such facilities to take advantage of the surpluses. Nonetheless, the surplus hydrogen produced in the Western and Eastern Regions today exceeds the demand of the complementary industries by a wide margin. This surplus has been estimated at 200 000 t per year;[56] this amount of hydrogen, from an energy perspective, is equivalent to 760 million litres of gasoline — enough fuel for a million light-duty fuel cell vehicles (see Appendix C).

Canada's hydrogen surplus, therefore, is a valuable asset to be deployed in the development of systems for fuelling hydrogen vehicles and power-generating facilities. Unfortunately, the locations that produce the surplus are often remote from the areas of projected demand, and, unless the quantities involved are very large, the cost of hydrogen increases rapidly with the distance it is moved.

A Short History of Hydrogen in Canada

In 1800, about 50 years before the first commercial oil well began production in Oil Springs, Ontario, hydrogen was being used in Europe for lighting, heating and cooking, in the form of "town gas" — a mixture of hydrogen, carbon monoxide and methane. The use of town gas grew rapidly during the first half of the 19th century, replacing the whale oil that had previously been used for lighting.[57] The first internal combustion engines, invented in 1860 by France's Etienne Lenoir, used town gas,[58] and in a sense were the original hydrogen ICEs; gasoline-powered ICEs would not appear for another 40 years.

As early as 1905, production of hydrogen from electricity was proposed by A.T. Stuart for the development of Niagara Falls. Fifty years later, with his son A.K. (Sandy) Stuart, the elder Stuart would establish the Electrolyser Corporation, now Stuart Energy.[59]

Coal gasifiers supplied Toronto with town gas until the end of the Second World War, when natural gas entered the market. Since then, hydrogen produced from natural gas has been used in the industrial gas sector for the hydro-treatment of fuels, fertilizer production, metal fabrication and glassmaking, as well as other applications.

Interest in hydrogen energy revived with the oil shocks of the 1970s, and Canada took a lead role in developing hydrogen-energy technologies. In 1984, and again in 2002, Canada hosted the World Hydrogen Energy Conference.

In 1987, the *Hydrogen National Mission for Canada* outlined a national vision for hydrogen as follows: [60]

> "Civilization will converge to a future profoundly shaped by electricity and hydrogen, using technologies which employ them best…. A unique mix of hydrogen needs, supply options and key technologies gives Canada an important competitive advantage at the beginning of the Hydrogen Age."

In view of the looming problems of energy supply and global warming, the *Mission* advocated the development of key hydrogen technologies. The years that followed saw major Canadian progress in these areas, including the Proton Exchange Membrane (PEM) fuel cell and innovative technologies for hydrogen production, handling and storage. Hydrogen systems incorporating Canadian technologies now lead the world.

There were other important initiatives as well. In 1989, for example, the European Commission and the Government of Quebec began the Euro-Québec Hydro-Hydrogen Pilot Project (EQHHPP). This dealt with the use of large-scale, low-cost hydroelectric generation of hydrogen for intercontinental transport to Europe, as well as development of utilization technologies. It also dealt with the testing and demonstration of hydrogen- and Hythane-powered urban buses and the development of liquid hydrogen storage systems.

This was followed in 1993 by the world's first fuel cell bus, a joint project involving Natural Resources Canada, the British Columbia government and Ballard Power Systems. During 1998–2000, progress continued in the form of the Ballard Bus Demonstration in Vancouver and Chicago, and Canadian participation in the California Fuel Cell Partnership. More recently, the hydrogen energy initiative in Manitoba is underway and involves several projects, as do the Hydrogen Highway and the Hydrogen Village initiatives in British Columbia and Toronto respectively.

5.2 Hydrogen System Technologies in Canada Today.

Canada is a world leader in Proton Exchange Membrane (PEM) fuel cells, electrolysis technology and hydrogen storage, and companies such as Stuart Energy Systems, Ballard Power Systems, Dynetek, and Hydrogenics are generating global interest in their hydrogen technologies. However, potentially competitive hydrogen and fuel cell technologies are being developed elsewhere, which means that Canada cannot afford to be complacent.

Profile of Hydrogen Industry in Canada (2003).[61]

- Number of people directly employed: 2 671;
- Revenues of sector: C$188 million;
- Research and development expenditures: C$280 million.

The Government of Canada, long aware of the potential of hydrogen and the need to retain the country's leadership in developing it, has been farsighted in supporting R&D for core hydrogen technologies. The 2003 federal budget announced funding of CAN$2 billion for initiatives related to climate change, of which CAN$215 million was allocated to the development and implementation of hydrogen and fuel cell technologies.

With potential economic opportunities in mind, the governments of Alberta, British Columbia, Manitoba, and Quebec have also made hydrogen a part of their energy and industrial development strategy. In brief:

- Alberta's *Strategic Research Plan*[62] sets out several research and development goals, including:
  - development of "clean coal" process technology;
  - research to improve the oil upgrading process;
  - a CO_2 storage program focused on using CO_2 for enhanced oil and gas recovery and extraction of coal-bed methane;
  - research to improve recovery from conventional and non-conventional resources while reducing energy intensity; and
  - developing a research infrastructure to support the emerging fuel cell industry and the hydrogen economy.

- British Columbia's *Hydrogen and Fuel Cell Strategy*[63] document depicts three development streams intended to position the province as a leading hydrogen economy by 2020. These streams are:
  - the "Hydrogen Highway," which will demonstrate hydrogen and fuel cell vehicles, hydrogen refuelling facilities and stationary power systems by the time of the 2010 Winter Olympic Games;
  - the development of a sustainable energy-technology cluster to deliver products and services, and secure high-value jobs; and
  - the revitalization of the province's resources to support hydrogen-based communities and industries, along with clean hydrogen production and distribution.

- Manitoba's *Hydrogen Economic Development Strategy*[64] focuses on five areas: hydrogen production, transportation, stationary and portable fuel cell applications, non-fuel applications and research. In the long term, the province's major hydroelectric resources, combined with water electrolysis technologies, may give it an important advantage in the production of clean hydrogen. For the near term, the strategy identifies niche applications as potentially viable; among the possibilities are:
  - transit buses and refuelling;
  - use of by-product hydrogen;
  - direct-to-DC electricity; and
  - hydrogen safety and systems design.

- Prince Edward Island's *Energy Framework and Renewable Energy Strategy*[65] document outlines a vision for its energy future based on energy conservation and renewable energy. It identifies wind/hydrogen as a potential part of the province's future energy systems and as one of its actions on climate change.

- Quebec has supported hydrogen initiatives for the last two decades, including the Hydrogen Industry Council, the Euro-Quebec Hydro-Hydrogen Pilot Project (EQHHPP), the International Standards for Hydrogen (ISO TC 197) and the Hydrogen Research Institute in Trois-Rivières. It continues to support the development and use of renewable energy sources such as hydro, wind and biomass. In other recent initiatives:
  - Phase I of a memorandum of understanding with regional developers in central Quebec was approved in 2003. This memorandum identifies hydrogen as an energy and industrial development priority. During the fall of 2004, the province expects to receive recommendations regarding priorities and projects for future hydrogen development.
  - Hearings will be held for thorough discussion of energy and environmental issues. This will likely result in specific actions to maintain support for research, development and implementation of hydrogen technologies.

As a result of such vigorous research and investments, Canada has already achieved significant progress in hydrogen applications, particularly in PEM fuel cells and in technologies associated with PEM-powered fuel cell vehicles. Research is now broadening to embrace a wider range of hydrogen and fuel cell technologies.

Despite substantial progress, however, the current state of hydrogen technology remains immature. In 1999, for example, it was predicted that commercial PEM FCVs would be available in five years. But the challenges of reliability and cost have proven to be more difficult than originally anticipated, and industry leaders now believe that the commercialization of hydrogen vehicles will occur between 2010 and 2015.[66] This has raised concerns about the prospects and timing of the commercial success of FCVs, with the result that investments in companies devoted to hydrogen and fuel cell technology have dropped to 10–20 percent of their peak values. The long time-to-market for hydrogen systems has discouraged private investment in the sector and led to the demise of several fuel cell and hydrogen start-up companies.

Some automobile companies are pursuing nearer-term combustion technologies.[67] Hydrogen-burning ICEs could play a transitional role if hydrogen can be produced cheaply enough and with sufficiently low emissions to overcome their problems with energy efficiency, which is less than that of projected fuel cell vehicles (see Appendix C). However, hydrogen ICEs will face challenges from incumbent technologies such as diesel hybrids and bio-fuels, and will need to compete with them on the basis of energy efficiency, emission levels, cost, refuelling availability and vehicle range.

5.3 The Market for Hydrogen and the Commercialization of Hydrogen Systems.

Hydrogen is an established industrial commodity. However, there are technology, market and cost barriers to using it as a common energy carrier.

One barrier is the relatively low cost of fossil fuels and their easy availability through an established, familiar infrastructure. Studies estimate that hydrogen delivered to the vehicle could cost CAN$3 to CAN$5 per kg, which is about two and three times the wholesale cost of gasoline on an energy-equivalent basis.[68] Moreover, even if hydrogen systems could compete directly in cost with fossil fuel systems, decarbonizing the hydrogen energy sources will also be required to achieve our emission objectives. As long as we assign no costs to the CO_2 emitted by our energy systems, these changes will come slowly.

The lack of public support for hydrogen systems, and scepticism about them, results partly from scanty public knowledge regarding energy systems, climate change and hydrogen. The public, being unfamiliar with hydrogen, is also concerned about safety. Demonstrations such as the 1998–2000 Ballard-British Columbia transit bus project have helped allay this concern, and more ambitious projects such as the Hydrogen Village and the Hydrogen Highway will generate greater confidence and engage a broader stakeholder base. Development of codes and standards, which started eight years ago with the establishment of the working group for ISO TC 197,[69] will help manage the risks, building on precedent-setting demonstrations.

International Standards Organization TC 197

ISO TC 197 governs standardization in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen. Canada's Bureau de Normalisation du Quebec (BNQ) provides the Secretariat for this standard. The BNQ is one of four Canadian standards organizations reporting to the Standards Council of Canada.

Fuel cells hold promise, but, as indicated earlier, their progress has not been as fast as predicted. However, as technology companies focus on markets other than vehicles, new revenue opportunities are appearing. Different fuel cell designs are being explored and new research efforts are finding solutions to previously intractable problems.

In summary, the market for hydrogen and hydrogen systems face substantial challenges. Nevertheless, Canada is fortunate in occupying an excellent leadership position, which we must strive to maintain.

6.0 Hydrogen Systems in the Future: Strategies to Start the Hydrogen Age.

Several obstacles stand in the way of a successful transition to the Hydrogen Age:

- First, hydrogen is an expensive form of energy. It will have to compete in the marketplace with incumbent energy carriers such as electricity and fossil fuels. Its GHG emission benefits will help it do this, but at present these benefits are not given sufficient monetary value to allow economics to drive wide-scale adoption of hydrogen as an energy currency.
- Second, hydrogen is viewed as an industrial commodity and there is little demand for it in non-industrial sectors. Consequently, no infrastructure has been built to make it easily available on a broad scale. Both this infrastructure and a market will have to be developed if hydrogen use is to become widespread.
- Third, the lack of a cost-competitive source of hydrogen has meant that hydrogen energy service technologies have been slow to develop. As a result, the product technologies for hydrogen systems are immature.

Because the sector with the largest potential impact for reducing GHG emissions is transportation, most effort so far has concentrated on the development of vehicular power systems. Hydrogen-powered transportation is thus likely to have the greatest potential for GHG reduction. Of course, other applications could lead the commercialization process, if they can deliver a higher value proposition, and thus support a higher cost to end users.

Unfortunately, developing an infrastructure to create a market demand can prove problematic and costly. For example, the attempt in North America to provide a fuelling infrastructure for natural gas vehicles ultimately proved fruitless, which makes it clear that the “build-it-and-they-will-come” approach does not always work. As a result, the development of a commercialized hydrogen supply infrastructure will most likely begin in localities where there are favourable market conditions, low-cost hydrogen sources and existing hydrogen-consuming services.

Recognizing the value of hydrogen systems by giving tangible credit to low-GHG energy sources will create an economic model that will accelerate adoption of these systems. But creating market demand depends on having proven, reliable, hydrogen-based products available. Environmental imperatives may ultimately demand a switch to hydrogen, but the emergence of this technology will occur sooner and more easily if its capabilities — measured in economics, convenience and performance — equal or exceed those of competing technologies. Achieving comparable or superior capability within niches, and then within sectors, is central to a healthy commercialization roll-out strategy.

A general strategy, therefore, must define emission objectives and then identify ways to meet these emission objectives in the light of energy source strategies, energy service technology development and market development strategies.

6.1 Meeting Emission Objectives in a Canadian Context.

Hydrogen, like electricity, is a highly versatile energy carrier and can be generated from any energy source. The emissions related to hydrogen in the energy system chain (measured as kg of CO_2 per unit of energy service), depend on how it is produced and delivered, and how efficiently it functions at the point of use. This makes it quite different from conventional fuels, which produce most of their emissions at the point-of-use stage of the fuel cycle. With hydrogen, by contrast, the emissions at this stage can be zero (when the hydrogen is used in fuel cells) or near-zero (when it is used in combustion systems with appropriate emission controls).[70]

Such emission levels can be achieved via several different paths. In these, CO_2 is either not produced in the energy system or is produced but not released into the atmosphere. For example:

- Water electrolysis, using electrical energy from hydro, nuclear, wind or solar sources, produces hydrogen with a reduction of 90 percent or greater in CO_2 emissions as compared with fuel cycle emissions from conventional energy carriers.
- Depending on the feedstock, generating hydrogen from fossil fuels and natural gas emits variable levels of CO_2 at the point of production. If this CO_2 can be captured and sequestered as it is generated, the emissions can be reduced by 90 percent using current technology (although long-range transportation of either the fuel or the CO_2 could add considerably to the net CO_2 emissions).

CO_2 Sequestration

There is good evidence that most of the CO_2 from fossil-fuel based, large-scale hydrogen production can be separated for sequestering. CO_2 has been successfully transported by pipeline for many years, and the design parameters are reasonably well understood. If sufficiently pure, CO_2 can be captured directly from the process stream.

There are three basic options for sequestering CO_2:

- underground storage in gas-tight natural reservoirs;
- deep-sea injection; and
- chemical reduction to solid carbon and carbon compounds.

Depleted oil and gas reservoirs and coal beds have the highest near-term potential for storing CO_2. These options also offer a potential economic return through enhanced production of oil, natural gas and coal-bed methane. The second and third options are not yet considered available, pending field testing to ensure minimal venting to the atmosphere.

Capture costs are still being established and are highly dependent on the purity of the process stream. Moreover, the long-term security of these storage techniques has not been addressed, nor has public acceptance of them been tested.

Future hydrogen production technologies could also have a net carbon-sink effect or could be part of a carbon-neutral fuel cycle.[71] Examples are biomass or the high-temperature, thermo-chemical processes being pursued in the U.S., Japan and Europe. Potential breakthrough technologies, involving direct solar conversion or biological processes, could also play a role in the longer term.[72]

At the point of use, hydrogen energy conversion is expected to yield higher efficiency than conventional processes. Electrochemical devices such as fuel cells could ultimately achieve a two-fold increase in efficiency over today's gasoline ICEs. These higher efficiencies would help reduce CO_2 emissions across the whole energy system.

The emissions from hydrogen production through current SMR processes are 12 kg of CO_2 per kg of hydrogen.[73] These are, on an energy basis, comparable to the emissions from gasoline. Because of the higher efficiency of a fuel cell vehicle, however, using SMR hydrogen in an FCV results in a 50 percent reduction in GHG emission per vehicle-kilometre travelled, relative to today's gasoline ICEs.

However, incumbent technologies are moving toward more efficient hybrid gasoline-electric and hybrid diesel-electric power sources, which are closing the efficiency gap (see Table 1). If hydrogen vehicles are to realize significant CO_2 reductions by the time they are commercialized, then new, lower-emission hydrogen supply systems will be required. These could be based on carbon-free energy sources such as nuclear, hydro, tidal or wind power, or from fossil fuel processes such as SMR with CO_2 capture and sequestration.

Table 1 - Comparison of Fuel, Power System Emission, and Efficiency.

Fuel and Power System	GHG emissions ($g\ CO_2$ / km)	Fuel consumption[74] (L or kg of H_2 /100 km)
E-H2 FCV (50% nuclear/50% hydro)	44.2	1.15 kg
E-H2 electric hybrid ICE (50% nuclear/50% hydro)	44.3	1.69 kg
SMR H2 forecourt FCV	151.4	1.15 kg
Diesel-electric hybrid	168.0	4.79 L
Gasoline ICE-electric hybrid	209.3	6.72 L
Gasoline ICE	301.2	10.30 L

In Table 1, the fuel consumption for each fuel pathway/vehicle is given in litres of liquid fuel per 100 km, or kg of hydrogen per 100 km, and has been determined over a standard driving cycle. The emissions are calculated on a life-cycle basis (for details, see Appendix C).

How Much Energy is There in 1 kg of Hydrogen?

1 kg of hydrogen ≈ 4.08 L of gasoline ≈ 3.74 Nm^3 (normal cubic meters) of natural gas, based on comparing the energy content of hydrogen with conventional fuels, on a higher heating-value basis. [75]

The emissions produced by the combustion of conventional fuels, including emissions from production, are:[76]

4.08 L of gasoline produces ≈ 10.4 kg of CO_2;

3.74 Nm^3 (normal cubic meters) of natural gas produces ≈ 8.1 kg of CO_2.

The efficiencies in Table 1 can be compared in the context of fuel consumption and the energy content in fuel (see sidebar, "How much energy is there in 1 kg of hydrogen?"). On this basis, fuel cell vehicles are projected to be twice as efficient as gasoline ICEs, based on the higher heating value of the fuel. When hydrogen ICE hybrids are compared with gasoline hybrids, the efficiency is almost the same.

In some segments of the transportation market, it may make sense to move to fuel cells through the intermediate step of fuelling ICEs with hydrogen or a hydrogen-methane mixture. Such a step could advance development of the hydrogen market and its delivery infrastructure. Because of the lower efficiency of hydrogen combustion compared to that of fuel cells, however, this would put additional pressure on developing the energy supply to achieve GHG emission benefits. Also, owing to the lower volumetric energy density of hydrogen relative to other fuels, the lower energy efficiency of combustion processes raises concerns regarding storage and range limitations. Perhaps because of this, only a few automotive manufacturers (notably Ford and BMW) are exploring hydrogen-fuelled ICEs. Most are concentrating on fuel cell systems.

6.2 Developing Hydrogen Production and Energy Source Strategies.

The basis for a successful hydrogen strategy is a comprehensive infrastructure plan that addresses energy source issues. In the short to medium term, we need energy sources that either use fossil fuels in conjunction with efficient carbon capture and sequestration, or are actually carbon-free.

In the long term, the development of hydrogen-electricity utilities will likely integrate hydrogen production and electricity generation to achieve desired emission characteristics. While there is risk involved in building infrastructure before achieving the widespread commercialization of hydrogen energy technologies, we can reduce this risk by building the infrastructure around existing industrial applications or by using small, on-site production systems.

The challenge for hydrogen in an energy-service market is to produce and distribute small quantities of hydrogen, relative to industrial standards, to many customers across a large geographical area. One approach is to evolve a production/distribution strategy by mapping the distribution of energy sources across Canada (see Figures 10 and 11).

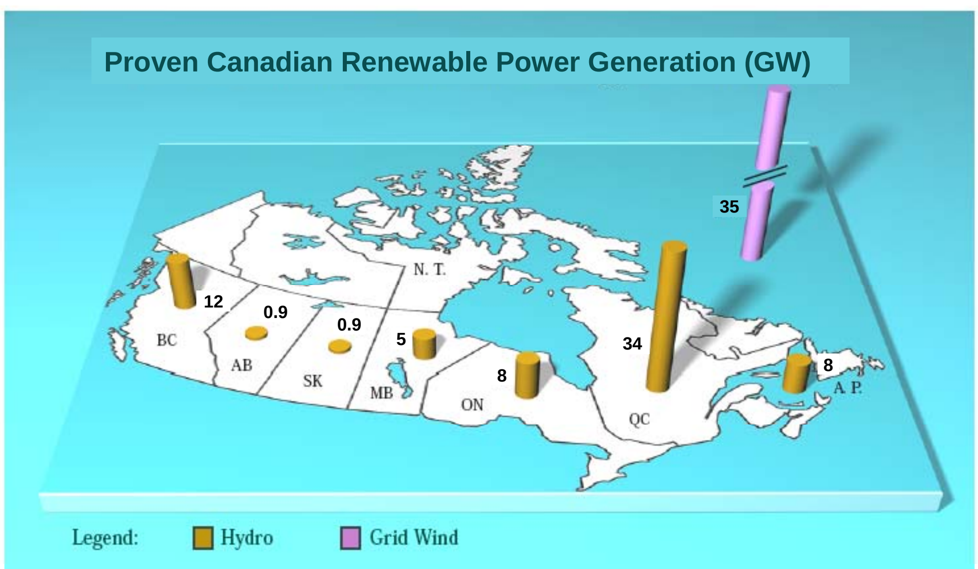


Figure 10 - Canadian Renewable Energy Stockpile.

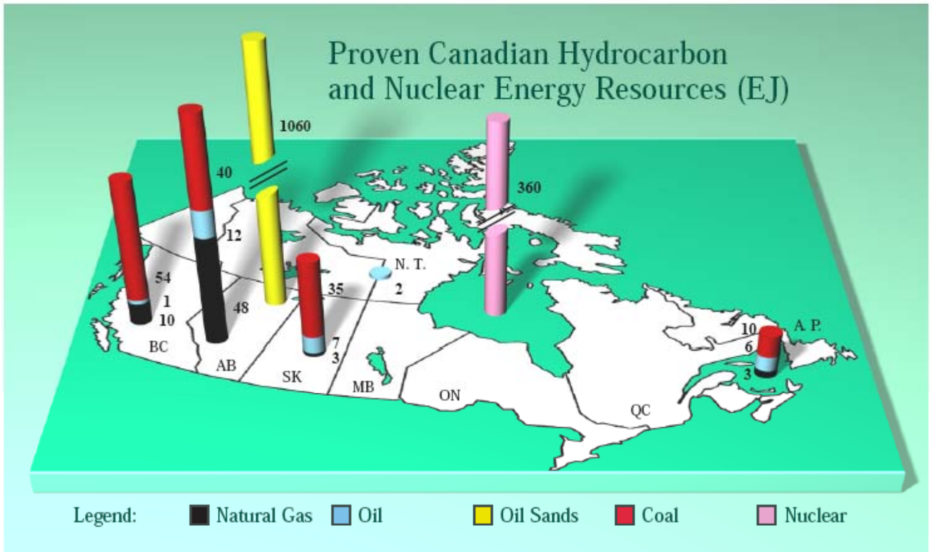


Figure 11 - Canadian Fossil and Nuclear Energy Reserves.

For example, hydrogen production from fossil resources could be developed in the Western and Atlantic Regions. Using nuclear energy for water electrolysis is most suitable where there is operating experience with nuclear plants, as in Ontario. Hydroelectric power, along with other renewable energy resources, could be exploited in Quebec, Manitoba and on both coasts. Wind energy would favour grids with hydro storage and control capabilities, as in Quebec and Manitoba. Use of biomass could play a role in all provinces.

Such a hydrogen infrastructure may eventually evolve to handle volumes of hydrogen so large that bulk transmission by pipeline between regions would become economically feasible. For example, hydrogen derived from fossil fuels will require carbon-management systems to achieve emission objectives. Depending on sequestration strategies, existing gas pipelines could be adapted so that hydrogen from western fossil resources could be sent to eastern markets, just as natural gas is distributed today.

Potential CO_2 sequestration sites in Canada generally lie near oil and gas deposits. If fossil fuels are processed close to the point of extraction, this presents an opportunity for low-cost sequestration. Deep saline aquifers are also potential CO_2 sinks and can be found in many locations.

The cost of capture and sequestration of CO_2 depends on many factors, including the purity of the CO_2 source and the quality of the site. For the oil sands, this cost has been estimated at CAN$75 per tonne of CO_2 (adding about 90 cents per kg to hydrogen production costs).[77] The cost may be less where sequestration can be used in enhanced oil recovery or in coal-bed methane extraction.

Preliminary analysis estimates the sequestration storage capacity of the Western Sedimentary Basin to be 36 000 Mt of CO_2.[78] At a sequestration rate of 100 Mt per year (appropriate for near-complete substitution of hydrogen for gasoline in the transport sector), this storage capacity is sufficient for 360 years (see Figure 12).

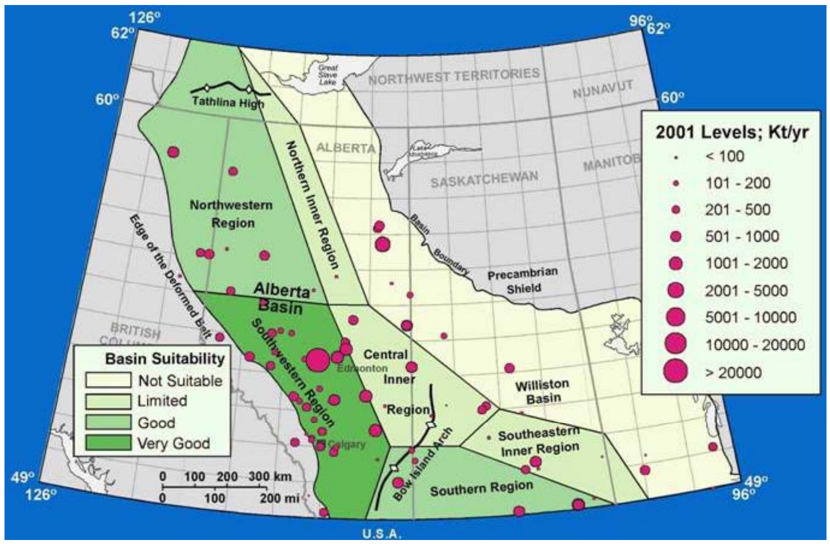


Figure 12 - CO_2 Sequestration Capacity of the Western Sedimentary Basin.[79]

6.2.1 Energy Source Strategies and the 1-Megatonne Analysis.

In the government's *Climate Change Plan for Canada*, hydrogen-fuelling technologies are identified as contributing a near-term reduction of 1 Mt of CO_2 per year. The following sections analyze some possible energy-source and hydrogen-supply strategies in the framework of achieving this reduction.

Definition of Time Frames

"Near term" is from now until 2012, the "period of the first commitment" in the *Climate Change Plan for Canada.*

"Medium term" is when the mass introduction of fuel cell vehicles is expected to occur and when the Hydrogen Age is in a rapid growth phase. The middle of this period is forecast to be around 2030.

"Long term" is when international treaties are forcing severe curtailment of anthropogenic GHG emissions, and global emissions have been reduced so that CO_2 concentration levels will stabilize. This period is expected to begin around 2050.

6.2.1.1 Hydrogen from Surplus Production.

A preliminary analysis indicates that 200 000 t of hydrogen are burned or vented in Canada every year.[80] Most of it is produced in the Western Region as a by-product of salt electrolysis plants (chlor-alkali and sodium chlorate processes) and would require some clean-up to remove impurities to meet hydrogen storage and fuel cell system requirements.

This amount of hydrogen, if captured, stored and transferred to the location where it was required, would fuel 1 million light-duty, fuel cell vehicles for a year, based on an average per-vehicle annual consumption of 200 kg.[81] The distance from the hydrogen source to the vehicle market could be a problem because of the transportation cost from remote locations of some of the production plants. In such cases, though, the hydrogen could provide a low-cost supply suitable for component and system testing, or it could be used for electricity generation either on site or for the grid (if connected).

The 1-Megatonne Analysis for Surplus Hydrogen

One Mt of CO_2 emissions could be avoided annually by using surplus hydrogen to displace 83 200 t of SMR hydrogen production (based on an SMR emission rate of 12 t of CO_2 per tonne of hydrogen produced). Using the same amount of hydrogen as a fuel would provide an approximate reduction of 0.86 Mt of CO_2, based on equivalent energy. This emission reduction could possibly double to 1.7 Mt, based on the higher efficiency of fuel cell hydrogen vehicles.

The same amount of hydrogen, if used for electricity generation by displacing a typical coal-fired generator (40 percent efficiency with respect to higher heating value (HHV)), with an emission rate of 1 kg/kWh, would result in a reduction of 1.3 Mt of CO_2 (assuming 40 percent efficiency based on HHV in the hydrogen-to-electricity conversion process).

6.2.1.2 Hydrogen from Clean Electricity Grids.

In the near term and continuing into the long term, provinces that currently derive most of their power from hydroelectric sources could produce clean hydrogen through grid-connected electrolysis. Manitoba, Quebec, Newfoundland and British Columbia fall into this category. The hydrogen produced by electrolysis could be used as a chemical feedstock as well as a vehicle fuel and for portable power applications.

Hydrogen production for use as a transportation fuel would represent a major new load on the electricity system, which could help finance expansion of clean electricity generating capacity. Because of the energy storage capability of hydrogen systems, hydrogen production could provide energy management services in the form of load levelling for grids to permit high penetration of intermittent or base-loaded generators.

Hydrogen produced and consumed through reversible electro-chemical devices could play a useful role in backup power applications and in ancillary services that would help balance the system. These hydrogen subsystems could also be integrated with fuel production for vehicles.

The 1-Megatonne Analysis for Clean Grids

Based on an average grid emission intensity of 0.05 t of C02 per MWh[82] and an electricity-to-hydrogen conversion rate of 55 kWh/kg of hydrogen, the emission rate for grid electrolysis would be approximately 2.75 kg of CO_2 per kg of hydrogen. A reduction of 1 Mt of CO_2 could be achieved through the production of 131 000 tonnes of electrolytic hydrogen, replacing 520 000 000 litres of gasoline on an energy basis.

Hydrogen fuel cell vehicles could potentially double this reduction to 2 Mt. At an electrolysis conversion rate of 55 kWh/kg, producing this amount of hydrogen would require 7,200 GWh of electricity. The amount of hydrogen produced would be sufficient to fuel approximately 655 000 vehicles, based on an annual fuel consumption of 200 kg of hydrogen per vehicle. The amount of electricity required is about 1 percent of Canada's total power generation during 2001, which was approximately 566.3 billion kilowatt hours (Bkwh). [83]

6.2.1.3 Hydrogen from Nuclear Energy.

In the medium and long term, nuclear energy could play a major role in developing Canada's hydrogen infrastructure. Because of the AECL Advanced CANDU Reactor (ACR), Canada holds a strong position if a near-term expansion of nuclear power in North America occurs. Preliminary cost analyses of hydrogen production, based on nuclear power with distributed electrolysis, shows that it could be competitive with central SMR.[84] Off-peak nuclear energy could be dedicated to producing hydrogen at the reactor for use as a chemical feedstock or for large transportation systems such as railways. Liquefaction might be needed to deliver hydrogen to such markets.

The 1-Megatonne Analysis for Nuclear Electrolysis

Based on an average CO_2 emission intensity of 0.015 t/MWh[85] and an electricity-to-hydrogen conversion rate of 55 kWh/kg, the emission rate for nuclear electrolysis would be 0.83 kg of CO_2 per kg of hydrogen. A 1-Mt CO_2 reduction could be achieved through the production of 104 000 t of electrolytic hydrogen, replacing 424 000 000 litres of gasoline on an energy basis.

This CO_2 reduction could potentially double to 2 Mt with the use of hydrogen fuel cell vehicles, as compared to today's gasoline ICE vehicles. At an electrolysis conversion rate of 55 kWh/kg, producing this amount of hydrogen would require 5,700 GWh of off-peak electricity.

6.2.1.4 Hydrogen from Renewable Electric Power.

In the near term, renewable forms of electric power generation will be coming on stream; these can be used to generate hydrogen with almost zero GHG emissions. Other than large-scale hydroelectric facilities, wind offers the lowest-cost renewable energy and is particularly attractive because it has the shortest lead time and the least environmental impact. This abundant resource could play a major role in developing a hydrogen infrastructure; hydrogen electrolysis from off-peak, wind-energy production is the ideal “dump load” that would allow more predictable dispatching of the generated energy.[86]

In the medium and long term, Canada's renewable energy resources will play a much larger role in the country's energy supply, and this will require major infrastructure developments. In the case of intermittent resources, such as wind and marine-current (tidal) energy, power must be gathered when it is available. Frequently, though, supply is out of phase with demand, so supply and demand management is required to balance the two; large-scale energy storage can help in this regard. However, optimizing the power grid to cope with such issues requires real-time measurement and control of very complex systems, and the methodology for this has still to be developed.

6.2.1.5 Hydrogen Production from Fossil Fuels.

In the near and medium term, the oil- and gas-producing regions of Alberta, British Columbia and Saskatchewan offer the opportunity of increasing demand for hydrogen production. On a per-capita basis, the oil and gas industries in these provinces are among the largest hydrogen producers in the world, generating 1.5 Mt annually. This is enough hydrogen to support 7 500 000 vehicles, based on an annual average fuel consumption of 200 kg per vehicle. Moreover, depending on whether oil upgrading is done by hydrogen addition or carbon rejection,[87] the existing hydrogen infrastructure could easily triple in size to meet the demands of the oil sands during the next two decades.

Offsets to CO_2 emissions in this sector can be achieved by the following actions:

- improving the recovery and efficiency of existing hydrogen production systems;

- capture and sequestration of the CO_2 emitted by hydrogen production from fossil fuels; and
- migration toward new hydrogen production processes that incorporate carbon sequestration or avoid net GHG emissions. Among such processes are the gasification of waste streams and electrolysis using clean electricity sources.

Carbon Capture and Sequestration from Hydrogen Plants

Because of the purity of the CO_2 they emit, and because they are close to suitable sequestration sites, SMR hydrogen plants in Western Canada are relatively attractive candidates for CO_2 capture and sequestration.

Sequestration costs depend on the choice of plant design and local CO_2 demand. Process design can affect CO_2 capture costs through the purity of the CO_2 stream and the efficiency of the process. Development of more efficient gas separation processes, which optimize hydrogen recovery as well as hydrogen quality and CO_2 concentration, will be a key to making CO_2 capture and sequestration practical.

Sequestration costs can also be offset by finding a market for the CO_2. A potentially large market would be CO_2 injection in oil fields and coal seams, aimed at enhanced oil recovery and coal-bed methane recovery.

Carbon sequestration is a technology under development, and demonstration projects are underway in Saskatchewan. The issue of public acceptance of large-scale CO_2 sequestration has not been addressed so far.

In the medium and long term, because of rising cost of natural gas due to depletion of North American natural gas reserves, hydrogen production processes may move away from SMR to oxygen-assisted gasification of coal, heavy oil or bitumen. This produces even more CO_2 per unit of hydrogen, but the CO_2 is fairly pure. The poly-generation gasification process (see Figure 10) is capable of providing a variety of energy services, including syngas, oil extraction and upgrading, and steam or hydrogen for power production. The CO_2 produced by the process can be captured and sequestered either in the hydrogen production process after the water-shift reaction or in the flue gas of downstream processes.

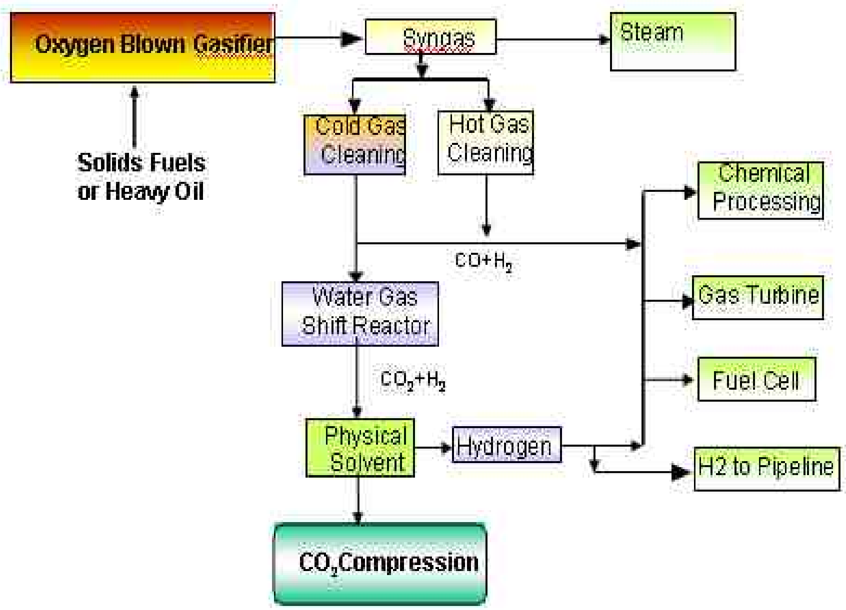


Figure 13 - The Poly-Generation Gasification Process.[88]

Construction costs for poly-generation gasification plants are high because of the size of the plants. However, given the rising hydrogen demands, plants on this scale may be needed in the oil sands. The resulting CO_2 emissions could be sequestered in the Western Sedimentary Basin or the saline aquifers lying below the Rocky Mountains.[89] The enormous amount of hydrogen produced could make an energy stream available for starting a general hydrogen-supply infrastructure.

In addition to the oxygen-assisted gasification process, other processes, such as the steam-iron cycle (HydroMax) process[90], could play a role and could use a wider range of feed-stocks, including waste biomass.

The 1-Megatonne Analysis for Hydrogen Production for Heavy Oil Upgrading

Production of hydrogen for heavy oil upgrading in Alberta is expected to increase from 0.92 to 2.92 Mt per year[91] during the near to medium term, creating an opportunity to build an infrastructure that would reduce emissions and supply hydrogen for local vehicles. Assuming that 2 Mt per year of new hydrogen production is supplied by SMR, and assuming an emission rate of 12 t of CO_2 per tonne of hydrogen produced, 1 Mt of CO_2 emissions could be avoided by:

- a 4.1 percent improvement in hydrogen recovery or in the energy efficiency of the hydrogen production process;
- capture and sequestration of 4.1 percent of CO_2 emissions; or
- diverting 4.3 percent of the hydrogen production (89 000 t per year) to electrolysis from a captive clean-electricity generator such as nuclear power (assuming an emission rate of .015 t/MWh). The CO_2 savings could be greater if the nuclear reactor were used to co-produce steam for heavy oil extraction, thereby avoiding the emissions from the combustion of fossil fuels. The oxygen from electrolysis could also be used in gasification processes

If emissions are sequestered or if hydrogen is produced using a non-fossil fuel process, hydrogen production could be expanded to include vehicles and stationary power sources.

6.2.1.6 Hydrogen from Biomass and Waste Streams.

Biomass, in the form of agricultural and wood wastes or purpose-grown crops, could be a feedstock for a number of hydrogen production processes. Among these are gasification, pyrolysis, bio-oil reforming, iron-steam hydrogen production and biological processes such as fermentation. If CO_2 capture is involved, the GHG reductions using biomass can exceed those of hydrogen pathways.

The amount of potential biomass in Canada has been estimated to be equivalent to 18–27 percent of oil production,[92] including 92 Mt of wood waste. Even today, biomass is estimated to fuel about 1,900 MW of electricity generation.[93]

The development of gasifiers for hydrogen production from biomass is at an early stage. The logistics involved in biomass collection and storage, and the seasonality of some resources, needs to be considered. However, there are several locations, particularly in the forestry industry, where a continuous supply of low-cost biomass is available.

The underlying issue in a biomass hydrogen strategy is whether a compelling case can be made for producing hydrogen from this resource, versus using the resource directly. The potential CO_2 reductions from producing hydrogen and sequestering CO_2, combined with the potential higher efficiency of hydrogen systems, need to be weighed against the increased cost of hydrogen production, purification and gas handling, and, as always, the collateral CO_2 emissions associated with the energy needed to transport feedstock and to dispose of CO_2.

The extent to which biomass can provide a significant hydrogen transportation fuel supply needs to be assessed. Initial work indicates there are challenges regarding impurities and costs in using biomass-to-hydrogen conversion to fuel

FCVs, particularly when weighed against the benefits of producing liquid bio-fuels for combustion processes.

For example (see Appendix C), a diesel hybrid fuelled with B20 (20 percent bio-diesel) could have lower emissions than an SMR-supplied FCV. Similarly, a diesel hybrid operating on Fisher-Tropsch diesel, using wood waste as the energy source could have lower GHG emissions than a hydrogen FCV using fuel from a non-carbon energy source (50 percent nuclear/50 percent hydro) — although, as a combustion system, it would emit pollutants such as NO_x.

6.2.3 General Development of the Hydrogen Energy System.

In the medium term, with an eventual 20 percent penetration of hydrogen vehicles into the new-car market in the U.S., providing hydrogen for fuel could present an important opportunity for a well-positioned Canadian energy industry. By this point, pipeline transmission of hydrogen to the U.S. market would begin to be economic.

By the medium term, the energy system will be more varied. It will comprise many more components than today, using various conversion and storage systems to link multiple energy sources such as biomass, wind, hydrocarbon, and nuclear. With greater use of renewables, different energy sources will be developed in different areas, which will be linked to a power grid that could be made efficient through new energy storage technologies.

Hydrogen will play a balancing role in the power generation and transmission sectors, optimizing the integration of base-loaded nuclear and intermittently renewable power sources.

The hydrogen infrastructure will develop according to the economics of energy supply and market demand, and could include static, large-scale cavern, chemical and possibly hydride storage facilities. Hydrogen may be moved as a gas, hydride, cryogenic liquid or, depending on the economics of the particular situation, by local distribution pipelines.

As the market for hydrogen expands, energy networks could be created in which renewable energy sources, nuclear energy sources and hydrogen production exist within a closed network on the existing electricity grid.[94] This could occur through the formation of utilities that would generate both hydrogen and electricity. Short-term hydrogen storage would be needed, but this would reduce the problems of matching electricity demand to intermittent sources such as solar and wind, and to base-load generators such as nuclear power. This would lead to higher market penetration of these forms of electricity generation, thereby reducing CO_2 emission intensity throughout the energy system.

6.3 Strategies for Developing Infrastructure and Hydrogen Energy Service Technologies.

Basic gaps exist in our knowledge of when the required technologies will be ready and when they might achieve cost targets. Even so, a comprehensive strategy must address the different parts of the hydrogen energy service chain, including:

- delivery systems and storage;
- end-use applications, including niche applications; and
- indirect technology accelerators.

6.3.1 Delivery Systems and Storage.

A key requirement of an energy carrier is that it be compact and have a high energy density. Hydrogen has a high gravimetric energy density (that is, it is light per unit of energy) but this is of limited value when its volumetric density is so low (it is bulky). The density can be increased by compression or liquefaction, but at significant economic and energy costs. On-site production could overcome the need for transporting hydrogen, but cost and emission problems need to be solved.

In the near term, several delivery options exist or are being developed. Assuming that high-grade hydrogen is needed (with purity meeting PEM fuel cell requirements) the delivery options include:

- Liquid hydrogen delivery and conversion to gaseous hydrogen for refuelling. A typical station consists of a liquid hydrogen tank, a liquid pump, a vaporizer and/or a hydrogen gas compressor.
- Regional or local hydrogen pipeline distribution systems connected to large SMRs with carbon sequestration, or to large-scale electrolysis facilities using low-CO_2 sources of electricity.
- On-site electrolysis powered by electricity derived from a source with low CO_2 emissions. A typical station consists of a connection to the electricity grid, an electrolysis hydrogen gas generator, purification equipment, a hydrogen compressor and gaseous hydrogen storage.
- On-site SMR with carbon capture and sequestration. A typical station consists of a steam methane reformer, a CO_2 capture unit, purification equipment, a hydrogen compressor and gaseous hydrogen storage.

Hydrogen could be delivered to the market through several channels. In addition to fleet fuelling, for which a dedicated fuelling station could be built at the vehicle terminal, hydrogen could be sold through retail outlets. Because real estate is a major cost in fuel distribution, existing fuel outlets are an obvious choice for this approach. However, since hydrogen can be produced on-site or shipped as a liquid, other retail channels might be used. One solution might be to expand the hydrogen infrastructure by using it to fuel equipment used to move goods, for example by providing hydrogen to power forklifts and delivery vehicles, and then expanding this distribution system to deliver hydrogen to retail outlets.[95]

Figure 14 - Hydrogen Fueling Station based on Electrolysis (courtesy of Stuart Energy Systems)

Perhaps the biggest challenge to be faced in hydrogen applications is hydrogen storage. To achieve the range of current gasoline ICE vehicles — about 480 km on a full tank — hydrogen vehicles demand storage capabilities that exceed the available technologies.[96] In the near term, current vehicle range expectations could only be met in platforms such as buses and delivery vehicles that can accommodate gaseous hydrogen storage. Discovery of new storage media would be very helpful, although much effort has so far produced no real breakthrough.

Alternatively, passenger vehicle platforms could be redesigned to accommodate compressed hydrogen storage or liquid hydrogen systems. Greater fuel efficiency, fuel cell hybrids, new fuelling methods and even different vehicle expectations ("city cars," for example) may reduce the need for large amounts of on-board hydrogen storage.

Figure 15 - High Pressure Hydrogen Storage (courtesy of Dynetek Industries).

Among the storage options are compressed gas at up to 700 bar (10 000 psi). Future improvements in hydrides and engineered nanostructures may be possible, which would provide competitive, low-pressure, on-board storage at ambient temperatures. Large-scale static storage, though, will continue to use liquid or high-pressure gas and, in the future, possibly metal hydrides.

In the near to medium term, home refuelling using small electrolysers could play a role. Small pipeline-distribution systems could develop in urban centres. Smaller reformers, incorporating carbon management, could also be developed.[97]

In the medium to long term, depending on distance and economics, hydrogen will be "moved" by wire (as electricity) or by pipeline. Other future storage and distribution possibilities are:

- improved liquefaction processes and cryogenic containment systems to allow on-board, liquid hydrogen storage and thermal energy recovery; and
- new adsorbent media that can compete with compressed gas and/or liquid storage, capable of ~ 6 percent hydrogen storage by weight or better.

6.3.2 End-Use Applications.

6.3.2.1 Transportation.

Hydrogen could be the key to reducing both global CO_2 emissions and criteria pollutants in transportation systems. Only electric storage batteries and hydrogen are able to deliver mobility with zero tailpipe emissions.

Several hydrogen technologies could be demonstrated and commercialized in the near term. Hydrogen ICEs, hydrogen ICE hybrids and the use of blended fuels — such as hydrogen with natural gas and hydrogen with diesel[98] — can offer near-term GHG reductions and improved efficiency, thus serving as transition technologies. However, while these technologies may play a commercial role in the near term, most automotive OEMs have concluded that fuel cell vehicles are the ultimate solution.

Figure 16 - Hydrogen Fuel Cell Vehicle (courtesy of Ballard Power Systems).

The duration of the transition period will be affected by improvements in incumbent technologies. Examples are improving fuel economy with battery-hybrid technologies or using other fuel solutions such as bio-fuels, which will raise the bar for market entry of hydrogen technologies.

In the near term, while the development and demonstration of FCVs proceeds, hydrogen ICEs could be commercialized for applications such as transit buses. The efficiency and cost of an optimized, high-compression hydrogen ICE could approach that of a diesel vehicle, if current U.S. Department of Energy (DOE) targets of 45 percent peak efficiency at a cost of US$30 per peak kW are met.[99] Powering a hybrid platform, the fuel efficiency of the high-compression hydrogen ICE hybrid could approach that of the diesel hybrid. Emissions from a hydrogen ICE, although not zero, are very low, with a greater than 99 percent reduction in CO_2 compared to fossil fuels. Developers are confident that the balance of the emissions will meet foreseeable emission regulations.[100]

If the hydrogen ICE is brought to market in the near term, the number of hydrogen vehicles in operation could soon reach the tens of thousands.[101] Penetration will likely be led by fleet vehicles — transit buses, courier, delivery and light-duty utility vehicles that refuel at a home base.

Figure 17 - Hydrogen ICE Shuttle Bus (courtesy of Ford Canada).

In the near term, fuel cells could be used in off-road vehicles and "light mobility products". These could be brought into the marketplace[102] as the leading edge of fuel cell vehicles.

If world development targets are met, hydrogen fuel cell vehicles are expected to be commercially ready in the time frame of 2015–2020. Some manufacturers, notably in the Japanese market, have projected a roll-out of tens of thousands of vehicles by 2010.[103]

In the medium term, the global penetration of hydrogen vehicles is expected to grow rapidly, pulling the hydrogen supply infrastructure along with it. The U.S. Department of Energy Posture Plan, for example, projects that the market share of hydrogen-powered new cars will grow from 4 percent in 2018 to 78 percent in 2030.[104] At the same time, as the availability of hydrogen grows, other applications such as rail links, jet aircraft and marine power systems will convert to it. This rapidly-expanding hydrogen infrastructure will bring new hydrogen producers and new distribution channels to the market.

In the medium and long term, hydrogen will be used in all new free-range vehicles; combustion engines will dominate flight applications and fuel cell systems will dominate ground transportation systems. In the long term, the ubiquity of hydrogen and fuel cells leads some experts to believe that transportation will converge with stationary power generation, allowing fuel cell vehicles to become electric power sources contributing to the electricity grid when not in use for transportation.[105]

Widespread adoption of hydrogen vehicles will encourage the growth of hydrogen infrastructure and create opportunities for product innovation, for further industrial uses of hydrogen and for an increasing range of energy services. Hydrogen will ultimately penetrate all markets, although at different rates depending on the market and application.

6.3.2.2 Stationary Power.

Applications for direct, stationary hydrogen power could include “energy stations” that combine distributed electricity generation and fuelling. In the near term, these could use hydrogen ICEs or fuel cells to serve as backup power applications.[106] In the medium term, when fuel cells achieve utility standards for operating life, they could serve as primary power generators using natural gas and carbon management, along with added hydrogen production for fuelling vehicles and other applications. Remote, off-grid population centres could integrate renewable electrical energy generation and hydrogen storage to convert an intermittent, primary-power source to a continuous supply of energy.

Figure 18 - Fuel Cell Backup Power System (courtesy of Hydrogenics Corporation).

In the near term, a potentially large application for such stationary power systems could be conversion of surplus hydrogen that is currently vented or flared into electricity, provided the cost of the conversion systems becomes affordable.

6.3.2.3 Chemical Feedstocks.

Low-emission, hydrogen-based infrastructures using SMR's with carbon sequestration, or electrolysis from low-emission and low-cost power, could supply hydrogen to established industrial applications such as ammonia and hydrogen peroxide manufacture. Ammonia production, for example, absorbs approximately 30 percent of Canada's hydrogen output, or about 900 000 t per year of SMR hydrogen production.[107] Such infrastructures could also support new hydrogen applications such as methanol synthesis from CO_2 streams[108] and the direct reduction of metals.[109]

6.3.3 Change Accelerators.

Commercialization in target and early-adopter market segments could be accelerated in a number of ways. One example would be the commercialization of component technologies and niche applications. Another would be an increased demand for fuel cells and other hydrogen technologies in export markets where these products hold a higher value proposition.

6.3.3.1 Niche Applications.

By encouraging the early commercialization of technologies, niche applications could play a strategic role in developing hydrogen infrastructures and energy systems. Such applications include forklifts and off-road vehicles; while these will not significantly reduce global CO_2 emissions, they can help create a market for products and assist in prototyping new technologies in controlled environments.

Niche applications could also encourage a volume of fuel cell manufacturing that would reduce product costs. Portable micro fuel cells and hydrogen-based backup power systems will also promote the use of hydrogen and help create new stakeholders in the hydrogen economy. In the short to medium term, hydrogen fuel cell vehicles and hydrogen ICE hybrid vehicles will allow vehicle applications to provide electric power services by connecting the vehicle electric power source to the electrical grid.[110]

Figure 19 - Off-road Applications (courtesy of General Hydrogen).

6.3.3.2 Export Potential and International Collaboration.

Hydrogen and fuel cell technologies will be commercialized in markets where they have the highest value proposition. Because of Canada's relatively low consumer energy prices and well-entrenched fuelling infrastructure, commercialization of applications is likely to occur in foreign markets first. In some of these foreign markets government tax policy has already recognized the real value of oil. This will create an export market for Canadian hydrogen technologies.

Hydrogen fuel cells could have a huge impact in developing economies, such as those of China and India, by improving efficiency, cutting energy consumption, reducing oil imports and improving air quality. The Asian region, which is experiencing a phenomenal growth in energy services, provides a possible opportunity to leapfrog conventional technologies, much as the cell phone did to telecommunications in these markets.

In the near term, Canadian hydrogen/natural gas technologies such as Hythane® could build on the existing natural gas vehicle infrastructure in regions such as Latin America and Asia, where there is a growing market for natural gas vehicles.[111]

Figure 20 - Hythane® Bus developed under Euro-Québec Hydro-Hydrogen Pilot Project. (courtesy of SunLine Transit).

Exports of hydrogen technology could also help Canada meet its emission objectives through the Kyoto Clean Development Mechanism (CDM), and help to create relationships with key trading partners in emerging hydrogen energy and technology markets.

6.3.3.3 Stationary Fuel Cells Using Natural Gas and Methanol.

In the near term, stationary fuel cells fuelled by natural gas and methanol could accelerate the commercialization of fuel cell technology for use in hydrogen applications such as fuel cell vehicles. This could have a significant impact on GHG emissions if carbon management or bio-fuels were used.

6.4 Market and Stakeholder Strategies.

6.4.1 Public Policy, Public Perception and Energy Market Design.

The public needs to be made more clearly aware about current levels of CO_2 emissions and their future implications. This will require more and better education about energy and the costs of adaptation to climate change. Wider public recognition of the issues will promote energy conservation and encourage the development of environmentally unobtrusive energy sources.

In the near term, the value proposition for hydrogen will grow with such education and will be reinforced by fiscal policies that provide incentives for adopting new technologies. Building clean-hydrogen infrastructures will be seen as a strategic policy objective by the government, and industrial hydrogen systems will be targeted to reduce CO_2 emissions.

Hydrogen initiatives will have to be assessed within the framework of changes to the whole energy system, “from source to service.” Government and commercial fleets will be a significant near-term market. Vehicle demand could be greatest in areas where air quality is poor, and where hydrogen vehicles could have a significant advantage over conventionally fuelled ones.

Concerns about the safety of hydrogen and the risks of commercializing it is another area where education is needed. Such concerns are actually the result of misunderstanding and lack of experience, and are not based on the intrinsic risk of using hydrogen as a fuel — in fact, recent mishaps involving hydrogen fuel confirm the industry view that hydrogen is at least as safe as conventional fuels, and perhaps safer.[112]

Codes and standards are one key to managing the risks of commercializing hydrogen technology. Another is to gain engineering experience with the properties of hydrogen versus those of other fuels. In the standards context, Canada is playing a major role in hydrogen standards development through its leadership of ISO TC 197. In the area of engineering, demonstrations such as the highly successful Ballard/British Columbia Transit Demonstration have already proved that public will readily accept hydrogen systems and can easily overcome the “*Hindenburg*” and “hydrogen bomb” misconceptions. Large-scale demonstrations are also planned for major population centers, such as the Hydrogen Highway™ in British Columbia (see Figure 21), the Hydrogen Village™ in Toronto and the proposed Hydrogen Airport in Montreal. Manitoba, Quebec, Alberta and Prince Edward Island are also considering important projects.

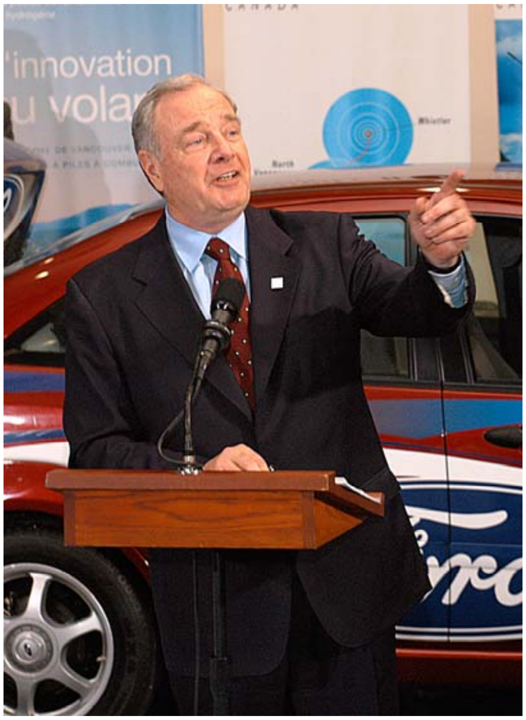


Figure 21 - Canada's Hydrogen Highway™ announced by Prime Minister Martin at the GLOBE 2004 in Vancouver.

Such demonstrations will help develop local expertise, bring hydrogen into public use, expand the base of stakeholders, debunk myths surrounding hydrogen and generally prepare the ground for consumer adoption of these technologies. In regions of high population density, these demonstrations can grow into economic market corridors such as the corridor from Vancouver to California.

In the medium term, incentives and energy taxes should be based on the cost of CO_2 reduction in other parts of the economy, which could be established through a cap-and-trade based CO_2-emission credit market. There will also be a move toward the full-cost accounting based on CO_2 capture and sequestration for particular applications, which will encourage conversion to cleaner alternatives**.** In the long term, regulations restricting or attaching a price on CO_2 emissions will be essential to guide the market to the desired low-emission outcome.

Finally, changes in the electricity market design will encourage the use of clean energy sources to co-produce hydrogen and electricity. Because hydrogen is a new energy carrier, the market will need time to adjust to its characteristics and maximize market efficiency. Hydrogen-electricity utilities will be formed to convert primary energy into both hydrogen and electricity, and will use the storage capability of hydrogen to complement the ephemeral nature of electricity. A hydrogen infrastructure will encourage independent producers, new distribution channels and new ways of providing power to the grid.

6.4.2 Stakeholder Analysis and Strategies for Building a Hydrogen Constituency.

On the whole, the benefits of hydrogen are neither sufficiently understood nor sufficiently valued to create a tipping point in the commercialization of hydrogen technologies. This stakeholder analysis suggests, however, that there is potential for change if the “help make it happen” groups develop an appreciation of the hydrogen economy. This can be achieved by proving the cost-effectiveness of the technology and showing that hydrogen is part of a comprehensive national strategy for establishing a sustainable energy system.

The most committed champions in the hydrogen constituency are the technology developers, some electrical utilities and certain power equipment suppliers who use primarily non-fossil energy sources. These groups, as a whole, have special expertise and knowledge of hydrogen and a financial stake in its success. In the narrow sense of the meaning of “stakeholder,” it is these groups who will determine the success or failure of hydrogen as a fuel.

The auto manufacturers are not perceived to be champions of hydrogen in the narrow sense, and are generally less committed to hydrogen as a fuel than they are to finding solutions to “sustainable transportation.”

Also in the group of “those who will help make it happen” are companies and institutions in the general supply chain; financial institutions are one example. These see hydrogen both as a solution to environmental issues and as a potential business opportunity. They are stakeholders in the broad sense and they wield political and financial power, which can play an enabling and supportive role.

The government is also in the “help make it happen” group; it is not committed to a hydrogen future, but views it as one of a number of alternatives to achieve its policy objectives. Environmental advocacy groups may also fall into this category, although not all are convinced that hydrogen has a role. For such advocacy groups, efforts should be made to demonstrate that hydrogen development is a long-term component of a comprehensive, sustainable energy strategy, and that hydrogen technologies can provide major environmental benefits.

The community of supportive and championing stakeholder groups is fragmented, reflecting the immaturity of the industry. There are conflicts within the sector itself, for example between nuclear and non-nuclear primary producers of energy, between proponents of different fuel cell designs, and between supporters of near-term action based on combustion engines and fuel cells.

The largest group of resistors is seen to be the oil companies, who hold a crucial stake in the incumbent fossil-fuel business. Although some oil companies have made investments in hydrogen technology and participate in the general development of the sector, North American oil companies (which are largely U.S. led) have been slow to embrace climate-change initiatives or consider hydrogen as a fuel. Because they control access to the existing retail fuel infrastructure, these oil companies hold a key position in the energy supply chain. However, development of transitional hydrogen technologies that meet near-term emission objectives within the oil and gas industries will create long-term prospects for hydrogen energy systems, and could provide a “win-win” strategy for gaining the support of the fossil fuel industry.

As for the general public, much of its apparent indifference results from a lack of awareness and education about climate change, and about hydrogen and energy systems choices.

6.5 Time Lines for the Hydrogen Age

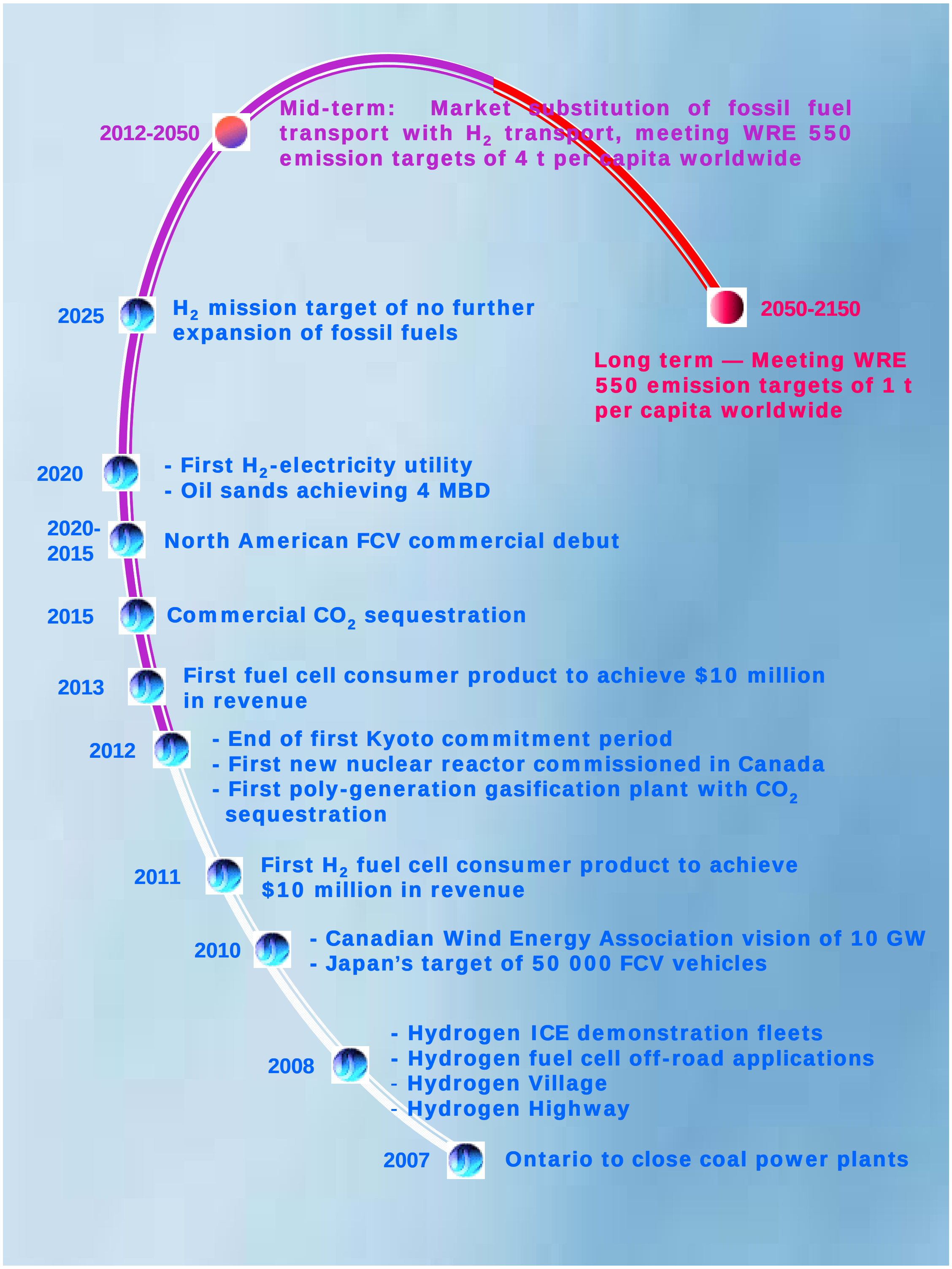


Figure 22 - A Timeline for the Hydrogen Age.

7.0 Action Plan and Recommendations.

7.1 Preparing for the Hydrogen Age.

By adopting hydrogen as an energy carrier to replace today's transportation fuels, the world economy can make a significant move towards stabilizing CO_2 concentrations while continuing to grow and prosper. Hydrogen technologies, complemented by the expansion of low-emission electricity production, will create systems in which the supply of energy services can evolve along sustainable pathways.

As the Hydrogen Age develops under increasing carbon emission constraints, these systems will shift from current hydrocarbon energy sources to new energy sources based on nuclear and renewable energy, and on fossil fuels with CO_2 sequestration. These systems will be designed and managed to achieve the GHG emission levels needed to mitigate climate change. Canada, because of its energy resources and technical expertise, can be among the leaders of this global transition.

The changes that hydrogen technologies will bring to our mobile and portable energy systems will be equivalent to transformation of society caused by introduction of electricity during the early 20th century. These changes will be the basis for an innovation boom in the energy services sector. Scalable, quiet, clean energy services derived from hydrogen will replace the gasoline- and diesel-based energy now used for transportation, resulting in cleaner air and better health for city dwellers.

However, the costs of moving to the Hydrogen Age will be large. Moreover, because sustainability is ultimately a worldwide social issue, the transition will require government direction within a framework of worldwide collaboration. Governments must therefore lead by creating a social and market framework in which the transition can occur. This must be guided by a clear vision of the desired end state — energy services that improve quality of life within a sustainable structure.

It is urgent that we establish a plan of action now, both because of the magnitude of the transition and because the increasing costs of adaptation to climate change may limit our future ability to act. The effects of greenhouse gases will be slow to take hold, but even with CO_2 emission reductions far beyond Kyoto targets, adaptation costs by 2050 are projected to be in the trillions of dollars and will inflict major dislocations on the world economy.[113] Acting early will not only reduce the impact of these effects, but will ensure that the hydrogen transformation is well underway by the time they become severe.

The transition to the Hydrogen Age will depend on market conditions, on the rate of development of service technologies and on consumer acceptance. Nevertheless, it will take decades, just as earlier changes in our energy systems took decades — the introduction of petroleum fuels (40 years), the development of the oil sands (50 years) and the introduction of nuclear power (30 years) are examples. In other words, if we expect hydrogen to play a significant role on a global scale by 2050, we have no time to lose. We must act quickly to address the critical issues that can hasten or slow the transition. The key actions required to carry out this change and accomplish the mission, as it is set out in this document, are discussed below.

7.1.1 Setting a National Mission to Meet Long-term Emission Targets.

Canada urgently needs an integrated national energy and climate change strategy that addresses the energy supply, the economy and the environment, and that sets the direction for future energy systems. It specifically needs to define the long-term emission targets, beyond those of Kyoto and within the context of a global plan, that will stabilize CO_2 emissions during this century.

Such government action should reflect the commitment of an informed majority of Canadians. To reach the necessary consensus, political leaders must give Canadians clear guidance on the implications of climate change, the future costs of adaptation and the need to change our energy future to meet long-term, globally determined emission objectives. For Canadians, this will mean reducing our per-capita emissions by about 60 to 80 percent during the next two generations.

The mission to “no longer expand the use of fossil fuels as energy carriers after 2025” establishes a tangible objective and sets the near- to medium-term dimension in which the changes should occur. Any related policy should embody a framework for achieving these reductions, including an economic framework for the cost of GHG emissions. The federal government, responsible for Canada’s climate change plan, and the provincial governments, responsible for our energy systems, need to work with the energy industry to ensure this transition. They can build on the initiatives already underway, such as the Large Final Emitters Program and the National Roundtable on the Environment and Economy.[114] The federal government should present Canada’s plan to the international community and help lead the way toward meeting global GHG emission objectives by 2050.

To accelerate future technology development, the benefits of CO_2 emissions mitigation must be assessed at the cost of controlling emissions in energy systems today — not at the market cost of the carbon sinks used to offset current emissions. The capture and sequestration of CO_2 from a large thermal power plant provides a practical scenario; within this framework, current technology places the cost at about CAN$75 per tonne of CO_2. Although these costs of mitigation are likely to fall with time, higher CO_2 charges in the early action period would be offset by the benefits of reducing GHG emissions sooner (thereby reducing their cumulative effect) and by the public health benefits of cutting power plant emissions other than CO_2.

Achieving the objectives of the mission will require a major shift in the way our society views and consumes energy, and will demand a fundamental re-engineering of our energy system to establish and reflect the value of sustainability. To make this possible, both energy system stakeholders and energy users will have to make commitments. Such a shift will become more likely and more imperative as the implications of climate change become more obvious.

However, while the *absolute* cost of energy will go up, the *relative* cost of energy services may not increase to the same degree, because more efficient and cleaner technologies will be brought on stream. Moreover, since Canada’s energy is cheap compared to that of most developed economies, the economic burden of changing our systems will be more easily carried by Canadians than by other populations.

Key Recommendations

Canada should implement an integrated Canadian energy and climate change strategy that goes beyond the current *Climate Change Plan* and sets the goal of meeting long-term, globally determined emission objectives. This implies an estimated, per-capita GHG emission reduction of 60-80 percent over “business as usual” by 2050. A government-industry task force, led at the federal level and including representatives from provincial energy ministries, the energy industry, academia and NGOs, should develop a national strategy for meeting emission objectives. Manitoba’s Energy Development Initiative should be explored as a potential model for industry-government collaboration.[115]

A framework for CO_2 emissions mitigation measures should also be created to stimulate the market for new, clean-energy technologies. Fiscal incentives, based on the current cost of managing CO_2 in fossil-based energy systems, should be established, and this should be in line with actions being developed by the Large Final Emitters Group.[116]

Re-engineering energy systems to address Canada’s emission objectives should become a national mission, and Canadians must be better informed about climate change if they are to become stakeholders in this mission.

7.1.2 Creating Stakeholders in a Hydrogen Future.

A strong and convincing case for a hydrogen future needs to be made to stakeholders in the current energy system. This group needs to assess the critical need and the potential impact that hydrogen could have in lowering emissions across the entire energy system, including oil and gas production in the near term, and transportation and electricity generation in the longer term. How hydrogen systems could best be integrated into the future design of energy markets should also be examined.

The oil and gas industry comprises an important group of potential stakeholders, as these companies are involved in the development of the oil sands. The creation of a hydrogen infrastructure for further expansion of the oil sands presents a tremendous near- and mid-term opportunity for curtailing GHG emissions in the oil upgrading process, while positioning the oil sands as a future source of hydrogen.

The electrical utilities comprise a second group of stakeholders, some of which are already developing hydrogen systems. Addressing our emission objectives will require them to choose among power sources such as nuclear plants, renewable energy including biomass, and fossil sources with carbon sequestration. These choices will depend partly on available local resources, and will create regionally distinct energy systems that will be well developed before hydrogen infrastructures are widely established. Planning is therefore required for the longer-term development of hydrogen infrastructure and production, and its smooth integration into energy market design.

Using the economic framework developed in the above-mentioned Canadian energy and climate change strategy, and working with groups such as the Large Final Emitters Group, industry should assess the competitive position of hydrogen versus other GHG mitigation measures in the energy supply chain. Such an analysis of hydrogen's role can also provide a benchmark for Canadian hydrogen systems against others and assess the competitiveness of various strategies. From this analysis, a set of cost/performance metrics and cost/performance goals can be derived for the hydrogen energy chain. These metrics and goals can be used to focus the Action Plan on acceptable priorities. This analysis is already under way as part of the Canadian Transportation Fuel Cell Alliance (CTFCA), but needs to be expanded to fully engage the energy industry and to consider competitive pathways for de-carbonising the energy chain.

Key Recommendations

The hydrogen and fuel cell industry, along with stakeholders from the Canadian power generation industry, and in partnership with governments, should carry out a competitive analysis of Canadian hydrogen deployment strategies. This would establish a starting point for potential future development priorities and establish targets and metrics for commercialization. The analysis should be done in the context of available options for GHG emission reductions, and relative to competing hydrogen strategies being developed by other countries.

The energy industry should also develop pathway analyses that examine the transformation of the current energy system into a system that uses hydrogen as a primary energy carrier for transportation and stationary applications. This information would feed into the analysis of Canadian hydrogen strategies.

To ensure progress, the hydrogen and fuel cell industry, along with a broader group that includes stakeholders in the energy industry, should function as a single voice and take responsibility for the Action Plan. This voice should represent industry, government and academics, and work in concert with existing initiatives such as those led by the Energy Dialogue Group and the Council of Energy Ministers.[117]

7.1.3 Establishing a Hydrogen Energy System as a Strategic Long-term Objective.

The government should explore the strategic role that hydrogen can play in Canada's energy future. In doing so, it should make the development and realization of the potential of hydrogen into a high priority long-term, strategic policy objective.

The government should increase public and private funding of basic technology developments that targets key areas such as PEM fuel cell materials and components, carbon sequestration, hydrogen storage and safety. This could be done through a national system of research centres in universities and through government and industry development projects, as well as through the international efforts to ensure that Canadian academia, industry and stakeholders have access to the best available technology. A system of peer review should be established to ensure program effectiveness.

Models such as the Knowledge Networks, proposed in the British Columbia Hydrogen and Fuel Cells plan,[118] could provide a model for a national network on hydrogen research, which would build awareness and interest in the academic community. The Canadian Hydrogen Association, through its technical meetings, has already played a leading role in providing this forum and could provide a starting point for organizing such a network.

The current mode of industry/university/government collaborative research also should be reviewed to ensure that it is effective in transferring technology to Canadian industry and in benefiting the Canadian economy.

Shaping a cultural shift toward sustainable development also requires educational initiatives at every level of learning. Government and industry should work together to develop course materials, programs and curricula that will create the workforce and the culture of innovation that we will need to compete in the Hydrogen Age.

As for cost, a realistic projection is that expenditures under this plan may grow to $200 million per year or more during the next ten years.

Key Recommendations

Canada should establish the long-term, strategic objective of making available to Canadian industry the best in hydrogen energy technologies and expertise. This can be ensured by funding technology development in industry and universities, by encouraging foreign enterprises to locate hydrogen development activities in Canada and by participating in global initiatives such as the International Partnership for the Hydrogen Economy (IPHE) and the International Energy Agency (IEA).

Wherever possible, the Government of Canada should enter into bilateral and multilateral agreements that will leverage Canadian expertise and investments to overcome the remaining technology barriers. Both the IPHE and IEA offer formal mechanisms by which nations can discuss and conclude such agreements.

The government, together with the hydrogen and energy industries, should create a technology plan that establishes technical goals. These may be based on rationalized metrics and targets that are similar to the U.S. Department of Energy's hydrogen program[119] and the U.K.'s Energy White Paper.[120]

A program is required to identify the workforce skills that will make Canada competitive in the Hydrogen Age and integrate these into our educational and training programs. Canada should also establish programs for supporting core technology development during the product development and implementation phase, and should consider new ways to streamline the proposal and funding process.

Finally, budgets should be determined for development of these measures. Such budgets should ensure that program costs are funded by the current energy system.

7.1.4 Action Plan for the Near-term Commercialization of Hydrogen Energy Systems in the Canadian Economy.

Accelerating the emergence of the hydrogen economy will involve near-term commercialization strategies and focused product development that will close technology gaps.

To position hydrogen as a visible mitigator of climate change, Canada should establish a target of 1 Mt of CO_2 reduction within the first Kyoto commitment period. Of this target, at least 100 Kt should come from pioneering transportation applications, beginning in those regions that can take advantage of low-GHG energy sources.

Technologies that could be commercialized in this time frame include hydrogen ICE and fuel cell vehicles in fleet applications. Other possibilities are power applications, off-road vehicles and portable fuel cells in high-value niche applications. In these early stages of market adoption, governments and energy companies should lead the market through fleet procurement. Such procurement would occur after a testing period, which would ensure that the technology meets the performance targets of the Action Plan.

The development and implementation of the advanced hydrogen production technologies and the development of carbon capture and sequestration systems should be undertaken in the oil and gas sector. The intent here is to prove these technologies for oil and gas production and to create a low-emission, hydrogen production infrastructure that meets the Action Plan's emission objectives. Along with using hydrogen surpluses to displace fossil fuels, these actions could help make up the balance of the 1-Mt reduction target of the first Kyoto commitment.

The Action Plan should balance near-term commercialization with the development of longer-range technologies, and should focus on overcoming the fundamental technical challenges we face today. Although the PEM fuel cell holds the lead and should receive the investment it needs for commercialization, other technologies can also play a role in developing infrastructure and energy services, and should be encouraged. These technologies include large-format, low-cost electrolysers (1 MW or larger), hydrogen production from biomass and from fossil fuels with CO_2 sequestration, gas separation and purification processes, fuelling station components, compressors, hydrogen ICEs and hydrogen storage systems. Delivery systems are needed that will address consumer concerns regarding gaseous fuels. Hydrogen storage targets must be reviewed to align vehicle requirements with the available storage options.

Demonstrations should be encouraged to promote the early adoption, testing and rapid prototyping of products in the development phase. The value of such demonstrations should be carefully weighed against the opportunity cost in technology development and downstream commercialization. Significant demonstrations should be leveraged within the international frameworks of the

IPHE and IEA and through joint projects between the U.S. Department of Energy and Canada's hydrogen programs.

To increase the market pull for hydrogen systems and gain the support of early adopters at the consumer level, hydrogen should move into the mainstream of sustainable energy options, energy conservation and renewable energy initiatives. The national mission of "no expansion of fossil fuels for energy services after 2025", is an objective that could be shared among the three initiatives: energy conservation, renewable energy and low GHG hydrogen systems.

Work on national regulations and international codes and standards should continue, both to speed up their implementation and to encourage wide acceptance of new hydrogen technologies within the global marketplace.

Key Recommendations

Industry, supported by government agencies, should develop a comprehensive commercialization plan to accelerate the product launch of hydrogen technologies. The emphasis should be on dealing with core technology issues related to achieving cost and performance targets.

The commercialization plan should analyze the benefits of early adoption of near-term hydrogen energy service technologies and the development of low-GHG hydrogen infrastructures in industrial markets — in the oil sands in particular — to determine how Canada could reduce GHG emissions by 1 Mt per year by 2012.

Demonstrations that have important scale and impact on high-priority markets, and which demonstrate the whole energy chain, should be undertaken and leveraged, wherever possible, through international programs

7.2 The 12-month Plan.

There are several specific actions that government, industry and academia can take during the next 12 months to ensure that the Action Plan maintains the desired direction and momentum.

The Federal Government, through the Hydrogen and Fuel Cell Committee (HFCC), can:

- begin a major economic analysis program to evaluate the cost/benefits of hydrogen technologies, as outlined in this plan, in comparison with other GHG reduction solutions;
- keep this evaluation current on an annual basis to reflect actual, and progressively more accurate, cost and benefit estimates;
- communicate to the energy industry the government's long-term goals for climate change — a 60–80 percent reduction in per-capita CO_2 emissions by 2050;
- commit to the mission of "no expansion for fossil fuels for energy services after 2025;"
- establish a framework for CO_2 accounting and ensure that this is considered in any energy project assessment;
- position hydrogen as a long-term, strategic objective of the Climate Change Plan;
- in partnership with industry, begin competitiveness analyses and energy system pathway analyses, including that of the bio-fuel pathway;
- assess the potential for biomass-to-hydrogen conversion and determine the depth of this resource;
- in partnership with industry and academia, begin preparing plans that will establish long-term strategic directions.
- allocate the funding needed to address the basic R&D requirements of the new energy system and to continue the major national programs that demonstrate it; and
- foster education of the general public regarding climate change, greenhouse gas emissions and possible solutions for their reduction.

Industry, through its industrial associations, can prepare a near-term commercialization plan to achieve 1 Mt of CO_2 reduction by 2012. This plan should include:

- a proposal for hydrogen ICEs;
- commercialization pathways for PEM fuel cell forklifts and other off-road vehicles;
- assessment of CO_2 capture and sequestration opportunities in hydrogen production for the oil sands;
- assessment of hydrogen for commuter train applications; and
- proposals to use surplus hydrogen to displace fossil fuels.

Some of the above projects are already underway. In a larger context, industry can also:

- undertake initiatives to harmonize international codes and standards;
- ensure that national regulations are aligned with commercialization efforts;
- in partnership with universities and governments, begin preparing plans to establish long-term strategic directions for technology development;
- advise on changes to R&D funding, intellectual property restrictions and technology transfer in government-assisted, industrial R&D; and
- recommend government budget priorities

Academia can:

- establish a plan to create a Canada-wide "knowledge network" to engage other members of the academic community and develop a national research review program;
- prepare outlines for educational materials for integration into school curricula; and
- in partnership with industry and governments, begin preparing plans that will establish long-term strategic directions.

7.3 The Action Plan and Canada's Hydrogen Future

Confronting the related challenges of GHG emissions, climate change and oil depletion is becoming an urgent matter. With every year that passes, more emissions enter the earth's atmosphere, adding to a CO_2 accumulation that is already exceptionally large.

While we cannot turn the clock back to achieve pre-industrial levels of atmospheric CO_2, it is certainly within our power to alleviate the worst effects of global warming — provided we act now. The Action Plan described above is a first step toward fulfilling Canada's domestic and global energy responsibilities, and will make us one of the leaders of the Hydrogen Age and the global shift to sustainable energy systems.

Appendix A: Origin and Development of the *Hydrogen Systems* Project

Work on the *Hydrogen Systems* project — originally called the *Hydrogen Road Map* project — began in June 2003, when it was recommended to the Hydrogen Technology Advisory Group (HyTAG) that a strategic plan be developed for Canada's transition to a hydrogen economy. HyTAG accepted this recommendation and a Project Charter was created late in 2003. Natural Resources Canada, the Canadian Hydrogen Association and the Hydrogen and Fuel Cell Co-ordinating Committee (HFCC) of the Government of Canada committed the necessary funding, and the project was approved by the HFCC in February 2004.

The Project Team formed to carry this out was led jointly by Matthew Fairlie, a private consultant and Senior Advisor to Stuart Energy Systems Corp., and Dr. Vesna Scepanovic, Hydrogen and Fuel Cells Program Manager for Natural Resources Canada. A Senior Advisory Panel was also appointed.

The first workshop, held in Ottawa in May 2004, involved a Core Team of hydrogen experts from government, industry and academia. This meeting produced a preliminary document entitled *Hydrogen Road Map for Canada Vision and Mission — Meeting the Greenhouse Gas Challenges: Kyoto and Beyond*. The *Road Map* was used as a briefing paper for a second workshop in July 2004; this workshop brought together the Hydrogen Strategic Plan Working Group, which was made up of a broad spectrum of stakeholders from government and industry. It is from the discussions and recommendations of the July 2004 meeting that *Hydrogen Systems: A Canadian Strategy for Greenhouse Gas Reduction and Economic Growth* has been written.

Natural Resources Canada, the Canadian Hydrogen Association and the Project Team would like to thank the Core Team and the Hydrogen Strategic Plan Working Group for their invaluable contributions to this document and to Canada's hydrogen energy future.

NRCan's DM George Anderson at Stakeholders Meeting, July 2004.

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Core Team: May 2004 Workshop

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Appendix B: Canada's Energy Resource Base.

Proven energy reserves for major energy sources for Canada and the world, assembled from a variety of sources, appear below. In the case of renewable sources the generating capacity was integrated over 100 years to provide a comparison with energy reserves for non-renewable (exhaustible) reserves. Potential reserves are much larger. The data was collected in June 2004, numbers may have changed reflecting new information.

Table 2 - Canada's Energy Inventory.

	Reserves	Reserves	Data Source
Natural Gas	**(Trillion cu ft)**	**(EJ fuel HHV)**	
Conventional Proven	60	64	capp.ca
Non-conventional Potential (including coal bed methane)	363	363	capp.ca
World Proven	5 501	5 900	bp.com
Oil	**(millions barrels)**	**(EJ fuel HHV)**	
Conventional Proven	4 500	27	capp.ca
Non-conventional Proven (oil sands)	174 000	1 060	capp.ca
Non-conventional Potential	300 000	1 830	capp.ca
World Proven	1 047 000	6 390	bp.com
Coal	**(billion tonnes)**	**(EJ fuel HHV)**	
Conventional Proven	7	138	coal.ca
Non-conventional potential	120	2 502	coal.ca
World Proven	984	20 660	bp.com
Nuclear	**(thousand tonnes)**	**(EJ fuel HHV)**	
Conventional Proven	600	360	AECL
Non-conventional potential (+)	1 800	8 000	AECL
World Proven	6 000	3 600	AECL

World Non-conventional potential (+ Thorium)	18 000	80 000	AECL
Large Hydro	**Capacity (GWh/y)**	**100 Y production (EJ – elect)**	
Capacity Proven (69 000 MW)	353 000	130	NER
Potential (160 000 MW)	819 000	301	NER
World Proven	2 650 000	975	NER
Grid Wind	**Capacity (GWh/y)**	**100 Y production**	
Capacity	750		CAN-WEA
Potential (100 000 MW @ 35% average capacity factor)	306 000	110	CAN-WEA
Total Proven (Canada)		**1 779**	
Total Proven (World)		**37 525**	

Energy Conversion Factors:

1 trillion cu ft gas = 1.07 10 ^{18} J `
1 barrel oil = 6.1 x10 ^{9} J
1 ton coal (bitmuous) = 3.2 x10 ^{10} J
1 ton coal (sub-bitmuous/lignite) = 1.0 x10 ^{10} J
1 EJ = 1.0 x10 ^{18} J

Appendix C: Energy System Emission Analysis.

The GHGenius model[121] was used to predict carbon dioxide-equivalent emissions for various fuel pathways. These emissions were estimated for the production and the use of fuel on a “source to service” basis and are calculated by the model in five fuel cycle segments: vehicle operation, fuel dispensing at the retail level, fuel storage and distribution at all stages, fuel production from raw materials and feedstock transport. Finished fuel transport is included in the fuel storage and distribution segment. A fleet size of 14.98 million LDV’s (small and large cars and light trucks) was used for the study, as this was the number of such vehicles in Canada in 2002.[122]

The vehicle operation baseline was derived using the performance projected for a 2010 Light Duty vehicle (LDV), weighing 1,160 kg, with a combined city/highway (55 percent/45 percent) gasoline consumption of 10.30 litres/100 km, or an equivalent diesel vehicle weighing 1,187 kg and using the same driving cycle with a petroleum diesel consumption of 7.28 litres/100 km. Both vehicle types were assumed to travel 17 000 km per year. At this rate of travel, the gasoline vehicle consumed 1,751 litres of reformulated gasoline per year and the diesel vehicle 1,238 litres of 30 ppm sulphur petroleum diesel per year.

Table 3, at the end of this appendix, gives the total grams of carbon dioxide (alone) that were emitted by various engines and fuel pathways with varying fuel feedstocks. For example, an “FT diesel w.w. hybrid” corresponds to wood waste feedstock producing Fischer-Tropsch (FT) distillate to fuel a diesel/battery hybrid LDV.

In Table 3, the fuel efficiency for each fuel pathway or vehicle is given in litres of liquid fuel per 100 km, or in kg of gaseous fuels per 100 km. The number of tonnes of CO_2 emitted per year is also listed, based on the 17 000 km traveled. The total CO_2 emitted by the entire LDV fleet is then given.

Next, the amount of fuel available per year is estimated. For hydrogen, reformulated gasoline, petroleum diesel and natural gas, it is assumed that the supply equals the demands of the complete LDV fleet. For other pathways, estimates of available fuel are based upon available feedstocks. For example, for wood waste converted to FT distillate, the amount of non-stem waste wood is 92 million tonnes per year.[123] Using process parameters for converting this wood waste, and assuming the use of the Choren process[124] requiring 4.2 kg of wood waste per litre of FT distillate, we can estimate an availability of 22.1 billion litres per year. Similarly, other biomass-to-fuel estimates give the availability of the listed fuel. (Further process parameters are listed below the table.)

The serviceable percentage of the LDV fleet can be estimated from the fuel availability figures. For hydrogen, reformulated gasoline, petroleum diesel and natural gas, the serviceability value is greater than 100 percent, since the fuel supply is estimated to be large. For those biomass fuels where the feedstock can be quantified, however, the serviceability of the fleet varies. For example, for a diesel hybrid LDV using FT distillate derived from wood waste, 179 percent of the fleet can potentially be fuelled.

Using the amount of CO_2 produced per year by a fuel pathway, and the serviceable percentage of the fleet, the table also calculates the LDV fleet's reduction of CO_2 (in Mt/year) from present production levels. For example, if all 14.98 million vehicles were diesel hybrids using the FT-diesel-from-wood-waste pathway, the emission of CO_2 would fall by nearly 68 Mt.

In the table's last column, the percentage of reduction in CO_2 emissions, compared to the case in which the whole fleet uses gasoline, is given. For example, for the FT-diesel-from-wood-waste pathway, the reduction is 88 percent.

Assumptions for Biomass-derived Fuel Pathways

Input data for GHGenius is available in various reports.[125] These provide data such as crop yields per acre per year, fertilizer requirements, herbicide requirements and energy requirements for cultivation, harvesting and transporting of feedstock. For the conversion process, data are also available for the weight of feedstock per volume of fuel produced. These data are given here for two example fuel pathways: wood-to-mixed-alcohols and wood-to-FT-distillate.

In Canada, two main sources of wood biomass exist: short-rotation forests, which are primarily willow trees, and wood waste, which is primarily the non-stem wood produced by lumbering. This non-stem wood waste includes branches and tree crowns, which are currently left in the forest.

Input data for these sources includes willow yields of 4.0 tonnes/acre/year in 1996, with a 0.1 percent growth rate per year. It is estimated that a total of 6.8 Mt of willow could be produced, based on available land in Canada. Fertilizer requirements per tonne of wood are 0.91 kg P_2O_5, 0.5 kg K_2O and 18.8 kg lime. Herbicide needs are 0.05 kg per tonne of wood, and energy requirements for cultivating and harvesting are 8.3 litres per tonne of wood. After harvesting, the wood is transported 80 km by truck. The finished fuel is transported 2,700 km by rail and 120 km by truck. For wood waste, fertilizer requirements are considered to be the same as for cultivated willow, since removing the waste from the forest also removes some natural nutrients.

The Enerkem process is used to convert wood to mixed alcohols (a demonstration plant has been set up in Sherbrooke, Quebec). This process gasifies the wood and then steam reforms it into liquid alcohols (methanol to pentanol, with ethanol being 48 percent by weight of all resulting alcohols). This process uses 3.2 kg of wood per litre of mixed alcohols. In the table, alcohols from this process are present in the M100, M85 wood waste and MA10 fuel pathways.

The Choren process, which has a demonstration plant in Europe, makes FT distillate from wood.[126] The process gasifies the wood and uses an iron catalyst to covert the syngas to liquid products. The process uses 4.22 kg of wood to produce 1 litre of FT distillate.

Other biomass feedstocks are available, such as landfill gas (LFG). It is estimated that Canada produces 21.9 Mt per year of LFG, which can produce methanol by the Hydrochem process.[127] Another potential feedstock is refuse-derived feedstock (RDF), which comes from municipal solid waste (MSW) and is estimated to have an availability of 4 Mt per year. With the Choren process, RDF produces 0.21 litres of FT distillate per kg; with the mixed-alcohol Enerkem process, it produces 0.13 litres of ethanol per kg.

Bio-diesel feedstock comes from canola, soy bean oil and beef tallow. However, these feedstocks are in extremely high demand for other production processes. Consequently, it is estimated that only 25 percent of the current production is available to make B20, which is a mixture of 20 percent bio-diesel and 80 percent petroleum diesel.

Ethanol can be made in a milling, cooking, and fermentation process from corn[128] or wheat,[129] or by the Iogen enzymatic hydrolysis process[130] from corn, wheat, or switch grass. Ethanol is present in E10 fuel.

Table 3 - Carbon Dioxide-Equivalent Emissions for Various Fuel Pathways. [131]

CO_2 Reduction for LDV's for Various Fuels in 2010								
	Per vehicle			LDV Fleet				
				Fuel				
Fuel & Engine	g CO_2 / km	Litre / 100 km	t CO_2 / yr	Mt CO_2 / yr	litres available / yr	Serviceable % of LDV fleet	Mt CO_2 reduction	% reduction
FT diesel w. w. hybrid	36.6	4.84 L	0.622	9.3	2.21E+10	179	67.38	88%
FT diesel w. w.	41.8	7.37 L	0.710	10.6	2.21E+10	118	66.07	86%
Hydrogen FCV	44.2	1.15 kg	0.752	11.3	2.92E+09	>100	65.44	85%
Hydrogen ICE hybrid	44.3	1.69 kg	0.754	11.3	4.30E+09	>100	65.41	85%
Hydrogen ICE	50.6	2.49 kg	0.861	12.9	6.35E+09	>100	63.81	83%
On-board M100 FCV	34.5	11.42 L	0.587	8.8	1.67E+10	57	38.99	51%
SMR NG forecourt FCV	151.4	4.19 L	2.573	38.6	1.07E+10	>100	38.30	50%
B20 hybrid	140.0	4.83 L	2.381	35.7	1.10E+10	89	36.73	48%
Diesel hybrid	168.0	4.79 L	2.856	42.8	1.22E+10	>100	33.92	44%
E10 hybrid	197.3	7.09 L	3.355	50.3	4.50E+10	249	26.45	34%
On-board M100 H2 ICE hybrid	44.4	16.57 L	0.755	11.3	1.67E+10	40	25.89	34%
Gasoline hybrid	209.3	6.72 L	3.559	53.3	1.71E+10	>100	23.39	30%
Methane CNG ICE	212.3	7.03 L	3.609	54.1	1.79E+10	>100	22.65	30%
On-board M100 ICE	50.4	24.85 L	0.857	12.8	1.67E+10	26	16.86	22%
B20 diesel	203.0	7.35 L	3.451	51.7	1.10E+10	59	14.69	19%
Diesel	243.6	7.28 L	4.141	62.0	1.85E+10	>100	14.67	19%
Methanol ICE M85 w. w.	117.7	16.61 L	2.000	30.0	1.04E+10	24	11.45	15%
Methanol ICE M85 LFG	117.0	16.61 L	1.989	29.8	7.29E+09	17	8.08	11%

FT diesel sf	-45.6	7.37 L	-0.775	-11.6	1.63E+09	9	7.67	10%
FT diesel sf hybrid	-31.4	4.83 L	-0.534	-8.0	6.80E+08	6	4.69	6%
MA10	283.8	10.54 L	4.825	72.3	1.37E+11	510	4.42	6%
E10 ICE	286.0	10.54L	4.862	72.8	4.50E+10	168	3.87	5%
FT diesel RDF	216.8	7.37 L	3.686	55.2	8.60E+08	5	0.98	1%
Methanol ICE M85 sf	68.8	16.61L	1.170	17.5	6.80E+08	2	0.95	1%
Gasoline	301.2	10.30 L	5.120	76.7	2.62E+10	>100	0.00	0%

Abbreviations and assumptions in the table

FCV: Fuel cell vehicle

ICE: Internal combustion engine

Hybrid: A hybrid vehicle using a gasoline or diesel engine to provide motive power and charge a battery system, which provides additional accelerative power.

B20: Diesel fuel blended with 20 percent of crop-derived bio-diesel fuel and 80 percent of petroleum diesel fuel. Canola, soy seed oil and tallow are feedstocks for bio-diesel fuel.

E10: A fuel blend of 10 percent ethanol and 90 percent gasoline. The source of ethanol can be crops such as corn, wheat or switch grass.

FT diesel w.w.: A diesel fuel distillate made by the Fischer-Tropsch process from wood waste feedstock.

FT diesel sf: A diesel fuel distillate made by the Fischer-Tropsch process from wood grown in a short-rotation forest. In Canada, woods that can be harvested in a relatively short time after planting are willow and poplar.

FT diesel RDF: A diesel fuel distillate made by the Fischer-Tropsch process from refuse-derived fuel (RDF). The RDF ultimately comes from municipal solid waste.

Hydrogen FCV, ICE, and ICE hybrid: hydrogen from electrolysis, with the electricity source half hydro and half nuclear.

M85 w.w.: a fuel blend of 85 percent methanol and 15 percent gasoline, where the source of methanol is wood waste.

M85 LFG: As for M85 w.w., except methanol is made by the Hydrochem process from landfill gas.

M85 sf: A fuel blend of 85 percent methanol and 15 percent gasoline, where methanol source is short-rotation forest wood.

MA10: A fuel blended from 10 percent mixed alcohols, in this case 10 percent ethanol and 90 percent gasoline. The process produces C1 to C5 alcohols, but predominantly methanol and ethanol if the feedstock is wood or agricultural waste.

On–board M100: 100 percent methanol fuel dispensed to the vehicle fuel tank and reformed on the vehicle to hydrogen. In this case, methanol is made by the Enerkem mixed-alcohol process from feedstock that can be wood waste, wood produced in a short rotation forest, landfill gas or agricultural waste. The CO_2 emissions are averaged from all four feedstocks, weighted by the proportions of the feedstock, which are 55 percent, 4 percent, 30 percent, and 11 percent respectively.

SMR NG forecourt: Hydrogen produced locally at the gas station by steam methane reforming of natural gas. Local production includes no transportation of hydrogen.

Glossary

BAU

“Business as usual.” The situation in which no action is taken to reduce GHG emissions or dependence on fossil fuels.

CANDU reactor

CANDU® stands for "CANada Deuterium Uranium." It is a Canadian-designed power reactor of PHWR type (Pressurized Heavy Water Reactor) that uses heavy water (deuterium oxide) for moderator and coolant, and natural uranium for fuel.

Carbon capture & sequestration

Capturing atmospheric carbon (carbon dioxide) and storing it in forests, soils, or ocean, or underground in depleted oil and gas reservoirs, coal seams and saline aquifers.

Choren processes

A set of processes developed by the Choren company to produce synthetic fuels.

Enerkem process

A process using advanced gas conditioning technologies to produce a clean synthetic alcohols from municipal waste residues and wood residues.

Fisher-Tropsch process

In this process, syngas, a mixture of hydrogen and carbon monoxide, is reacted in the presence of an iron or cobalt catalyst to produce such products as methane, synthetic gasoline and alcohols, with water or carbon dioxide as by-products.

GHGenius

GHGenius is a modelling tool developed for Natural Resources Canada. It is based on the 1998 version of Dr. Mark Delucchi’s Lifecycle Emissions Model (LEM). GHGenius is capable of analyzing the emissions of many contaminants associated with the production and use of traditional and alternative transportation fuels

Greenhouse gases (GHGs)

Greenhouse gases contribute to global warming by trapping heat in the earth's atmosphere. The chief greenhouse gas is carbon dioxide; others include methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride.

Gt (gigatonne)

One gigatonne equals 1 billion tonnes.

HydroMax

The HydroMax Technology is a two-step, hydrogen production process that injects steam into a bath of molten iron within a reactor vessel. The oxygen in the steam reacts with the iron, releasing hydrogen and forming iron oxide. Hydrogen production continues until the availability of unreacted iron is at a low level. Adding a carbon reductant such as coal then reduces the oxidized iron back to iron.

Intergovernmental Panel on Climate Change (IPCC)

The IPCC was established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) to assess scientific, technical and socio- economic information relevant for the understanding of climate change, its potential impacts and options for adaptation and mitigation.

International Energy Agency (IEA)

The IEA was established in 1974 to foster collaboration among its member countries and the global community for economic development, energy security, environmental protection and human well-being.

International Partnership for the Hydrogen Economy (IPHE)

The IPHE serves as a mechanism to organize and implement effective, efficient, and focused international research, development, demonstration and commercial utilization activities related to hydrogen and fuel cell technologies. It also provides a forum for advancing policies and common codes and standards that can accelerate the cost-effective transition to a global hydrogen economy.

Iogen enzymatic hydrolysis process

A process that uses enzyme hydrolysis to convert the cellulose in agriculture residues into sugars. These sugars are fermented and distilled into ethanol fuel using conventional ethanol distillation technology.

Kyoto Protocol

Under the Kyoto Protocol, industrialised countries and those in transition to a market economy (the so-called "Annex I countries") have agreed to limit or reduce their emissions of greenhouse gases. The Protocol sets quantified emission limitations and reduction obligations with respect to a basket of six gases. Of these, carbon dioxide, which derives from the burning of fossil fuels such as coal, oil and gas, is the most important.

Molten Carbonate Fuel Cell (MCFC)

The MCFC uses a molten alkali carbonate mixture as an electrolyte, retained in a matrix. They operate at a temperature of about 650°C, producing useful heat. In this case the cathode must be supplied with carbon dioxide, which reacts with the oxygen and electrons to form carbonate ions, which carry the ionic current through the electrolyte. At the anode these ions are consumed in the oxidation of hydrogen, which also forms water vapour and carbon dioxide to be transferred back to the cathode.

Large Final Emitters Group

The Large Final Emitters Group of Natural Resources Canada was established in late 2002 and is responsible for working with key industry sectors to reduce annual greenhouse gas emissions.

Mt (megatonne)

One megatonne equals 1,000,000,000 kg.

Organisation for Economic Co-operation and Development (OECD)

The OECD groups 30 member countries into a forum that discusses, develops and refines economic and social policies.

ppm

Parts per million (by volume)

Proton Exchange Membrane Fuel Cell (PEM Fuel Cell)

Also known as the Solid Polymer Fuel Cell (SPFC), the PEM FC electrolyte consists of a layer of solid polymer that allows protons to be transmitted from one face to the other. It requires hydrogen and oxygen as its inputs, though the oxidant may also be ambient air, and these gases must be humidified. It operates at temperatures of around 90°C because of the limitations imposed by the thermal properties of the membrane. The PEM FC can be contaminated by carbon monoxide, reducing the performance by several percent for contaminant in the fuel in ranges of tens of percent. It requires cooling and management of the exhaust water in order to function properly.

Solid Oxide Fuel Cell (SOFC)

A SOFC uses yttria-stabilised zirconia as its electrolyte, sandwiched between the anode and the cathode. It runs at a temperature of around 1,000°C. The heat produced can be used in cogeneration applications or in a steam turbine to provide more electricity than that generated from the chemical reaction within the fuel cell. Several different fuels can be used, from pure hydrogen to methane to carbon monoxide, and the nature of the emissions from the fuel cell will vary correspondingly with the fuel mix.

Steam methane reforming (SMR)

In steam-methane reforming, desulfurized gases are mixed with superheated steam and reformed in tubes containing a nickel base catalyst. The reformed gas, which consists of steam, hydrogen, carbon monoxide, and carbon dioxide, is cooled and passed through converters containing an iron catalyst where the carbon monoxide reacts with steam to form carbon dioxide and more hydrogen. The carbon dioxide is removed by amine washing.

WRE 550 Scenario

An IPCC scenario for global CO_2 stabilization that depends on achieving an atmospheric CO_2 level of 550 ppm. So named because it uses one of the stabilization paths developed by Wigley, Richels and Edmonds.

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