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HYDROGEN AND NUCLEAR ENERGY:

BUILDING NON-CARBON BRIDGES TO THE FUTURE

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Abstract

The current world-wide emphasis on reducing greenhouse gas (GHG) emissions provides an opportunity to revisit how energy is produced and used, consistent with the need for human and economic growth. Both the scale of the problem and the efforts needed for its resolution are extremely large. We argue that GHG reduction strategies must include a greater penetration of electricity into areas, such as transportation, that have been the almost exclusive domain of fossil fuels. An opportunity for electricity to displace fossil fuel use is through electrolytic production of hydrogen. Nuclear power is a large-scale commercially proven non-carbon electricity generation source. It can also provide the high-capacity base needed to stabilize electricity grids in conjunction with hydraulic and other stored energy systems. Energy storage is essential to accommodate low capacity factor non-carbon sources such as wind and solar. Electricity can be used directly to power stand-alone hydrogen production facilities. The hydrogen streams can be processed to very economically recover deuterium that can be re-oxidized to heavy water. This establishes a unique economic synergy with the CANDU® reactor system which requires heavy water as a major material component.

World-wide experience shows that nuclear power can achieve high standards of public safety,

environmental protection and commercially competitive economics, and must be an integral part of future energy systems.

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Hydrogen And Nuclear Energy:
Building Non-Carbon Bridges To The Future

Introduction: The Need For Synergistic Approaches

We need to manage the environment of our planet, so that we may continue to live on it. Man is affecting the environment in a significant and sometimes worrisome way. The effects of humans on the environment are becoming clear, by whatever measure is used (population, temperature, species count, deforestation, atmospheric gas concentrations, freshwater sources, etc.). Some of the environmental problems identified, such as pollution of the ocean and atmosphere, transcend national boundaries. It is difficult for governments to take actions to protect these global commons; this very lack of action may adversely affect the economic and political survival of all nations. Much of this ground has been covered elsewhere: we focus on issues associated with man’s use of energy. Many of the problems identified, in particular increasing levels of greenhouse gases in the atmosphere, are attributed to the use of energy. Energy use, per se, is not fundamentally contrary to protection of the environment. It is the uncontrolled release of products associated with energy production and use that can adversely affect the environment. In fact, man’s harnessing of energy sources can be directed to improvement of the environment. We now have a real opportunity to revisit how we produce and use energy, consistent with the need for human and economic growth and protection of the global commons.

The recent global and national debate on reducing and hence managing greenhouse gases and other emissions has centred on a number of issues. The real problem is to find ways to reduce the effects of emissions without requiring onerous or expensive restrictions on needed industrial or economic growth, and to find feasible ways to enhance emissions management technology. If industrial processes become more expensive then one cannot compete in a global economy; therefore, market forces and consumer needs have to be also included. But there is no consensus on how to achieve effective management of our shared environment, only a realization that something must be done. This realization has spawned many and varied research programs to enhance energy efficiency and to reduce emissions.

Thus "Green" initiatives include development of sustainable or eco-friendly growth, growth with the minimum impact on the environment. However, many of these initiatives are costly: they require drastic changes in social, economic and energy use patterns, and would imply or call for a return to a more eco-friendly or "simpler" society. Either indirectly through added costs or directly through relinquishing elements of current lifestyle, this simpler society can easily be a poorer one. The proposed measures include increased taxation, more restrictive laws, mandated reductions in energy use, and large increases in end-use energy efficiency (Suzuki Foundation and the Pembina Institute,1998). Indeed, the Canadian Government has explicitly advocated significant change such that:

> "All Canadians need to make changes in the way they generate and use energy, how they move people and goods, how they heat their homes, and how they produce goods. With this in mind, NRCan's climate change efforts are aimed at moving the market toward improved energy efficiency, developing alternative energy markets and focusing R&D resources on providing technology solutions to this global challenge."
>
> Energy: Exploring New Avenues In Energy Efficiency
> Source:http://www.nrcan.gc.ca/gcc/english/html/feature/energy.html

None of this is new. The reason for concern over the potential outcome from such a program is apparent from Figure 1. To date, growth of the World economy expressed as the Gross World Product (GWP), is highly correlated with the measured growth of CO_2 concentrations in the atmosphere, unsurprisingly so since world economic growth in the 20^{th} century has been based on carbon fuels. No country is immune: Canadian growth shows the same trend (see Figure 2), as one would expect for a country so dependent on world trade. Since economic growth is so tightly coupled to energy production, unthinking reduction in energy production could very easily lead to grim economic consequences. Conversely an awareness of this effect could provide a powerful constraint on policies to reduce greenhouse gas emissions. The obvious way of escaping this dilemma would be to deploy technology that decouples energy production from greenhouse gas emissions. Without intelligent use of technology, any country attempting significant (beyond nominal, voluntary measures) restrictions on emissions would likely experience a totally unacceptable economic effect (Imperial Oil, 1998).

Solutions and measures that would undermine national economies and threaten the survival of large corporations are surely not what is wanted considering the other large changes that most people would regard as unavoidable. Thus there is a generally accepted need for substantial, continuing growth in the world’s developing economies. Then, the world’s economies are going to have to bear both costs of whatever adaptations are made to reduce greenhouse gas emissions for the long-term and, likely, interim costs to offset the cumulative effects of the emissions. Policies that would achieve a 1% reduction in the GHG concentration in the atmosphere through a 1% reduction in the world product and world trade are surely unworkable.

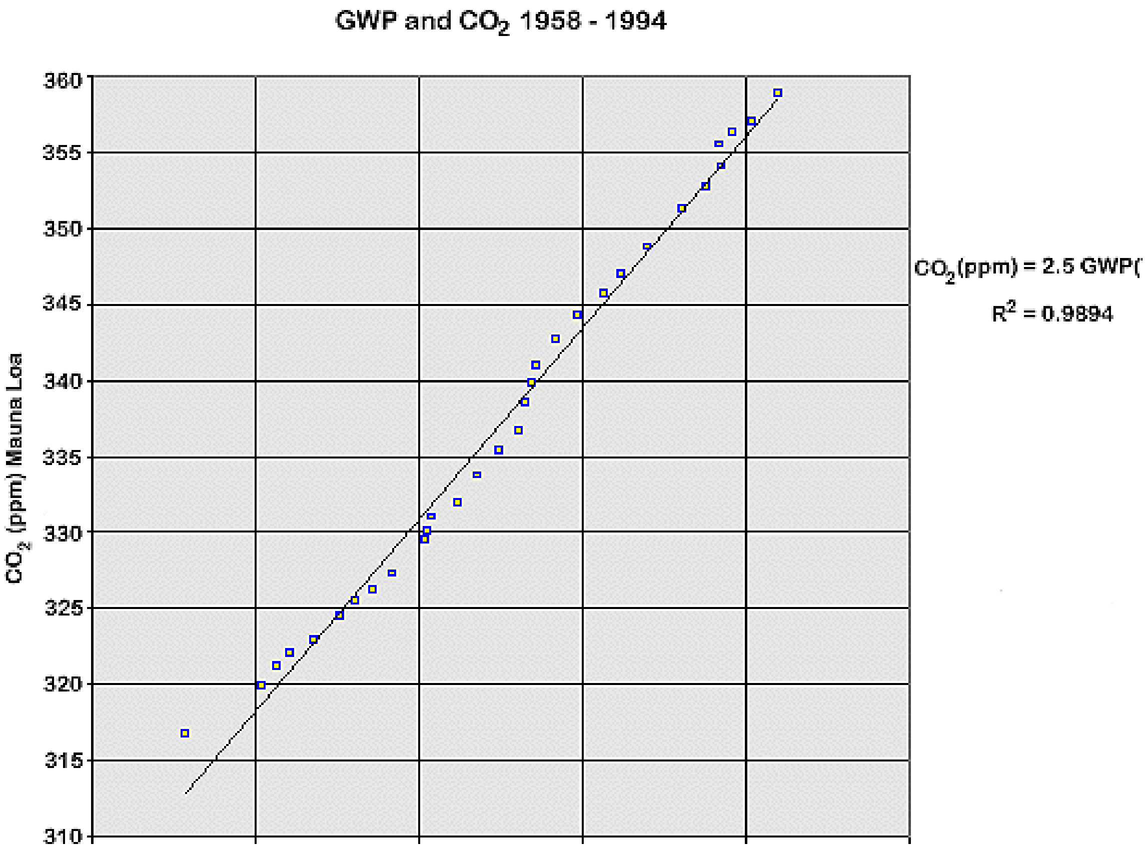


Figure 1: Global Economic and Atmospheric CO_2 Concentration Trends

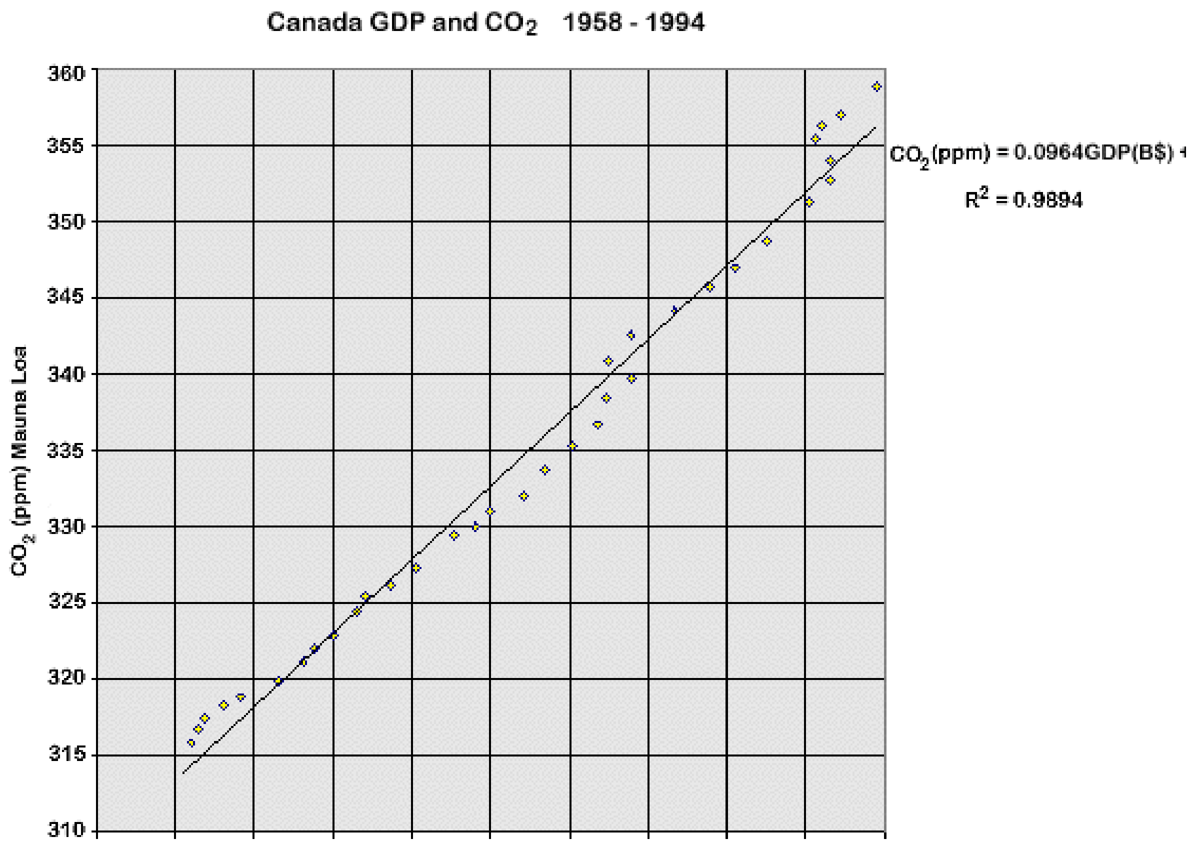


Figure 2: Canadian Economic and Atmospheric CO_2 Concentration Trends

If that is the only option on offer, it is hardly surprising that emissions in Canada continue to grow steadily (see Figure 3) and are projected to maintain this trend. Energy-intensive industries are clearly "emitters", with many kinds of waste streams. As shown in Figure 4, unrestrained open-market use of both petroleum and natural-gas continue to grow, and hence lead, inexorably, to increased GHG emissions.

Just as an individual’s or a nation’s wealth is expressed in various "currencies", various "energy currencies" are used (Scott, 1994-1996). Some of these (e.g., oil and natural-gas, coal, hydraulic, nuclear, wind and solar) are primary forms of "energy wealth". In developed societies in particular, these are extensively converted into more convenient forms of "energy currency" (e.g., refined liquid fuels and electricity as well as, less obviously, every conceivable form of finished goods). To avoid reduction in energy wealth and all the adverse effects that this would entail, we need to concentrate on ways to displace the GHG-emitting primary energy sources with sources that are zero or near-zero GHG emitters. Those sources are nuclear, solar, wind, hydraulic and other renewables. Apart from possible minor direct use of solar energy in portable devices, these are stationary energy sources. They can reduce emissions in the electricity generation sector but cannot directly influence almost all of the transportation sector and substantial parts of the industrial sector, together responsible for almost half the total GHG emissions (see Figure 3). The consequences of this limitation are even larger than they seem since a substantial part of the remaining GHG sources (e.g., space heating) occur as ill-distributed demands that are best addressed by energy currencies that are easily stored.

To avoid all the adverse effects of throttling these parts of the global economies, we must add a flexible, storable energy currency to deployment of more of the near-zero GHG electric sources. Rechargeable batteries have been the subject of huge development efforts without producing a significant breakthrough in the prospects for storage of electricity in these electrochemical forms. While electrochemical cells will likely grow slowly as an energy currency, it is hydrogen, particularly when used in a fuel cell, that seems to offer the most as an alternative energy currency.

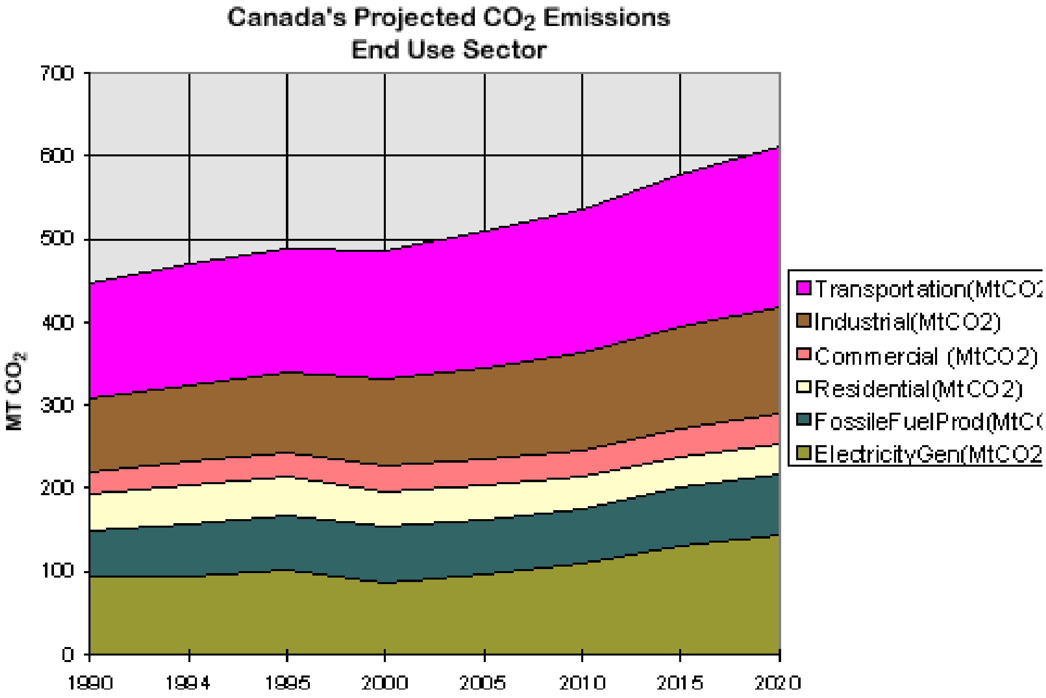


Figure 3: Projections for the Future

Although the opportunity for hydrogen is not necessarily confined to transportation, it is transportation that provides the largest opportunity for the synergism of hydrogen and near-zero GHG electricity. The extensive US study on this topic (Berry, 1996) states that: "As the ultimate fuel, hydrogen, once established, will provide a single transition to a stable alternative fuel, protecting long-term development and investment in alternative-fuel vehicles and infrastructure...a transition to hydrogen vehicles…would last for the foreseeable future".

So for transportation, if we are to provide consumer choice, efficient open markets, and reduce emissions, how do we also balance and meet the global requirements?

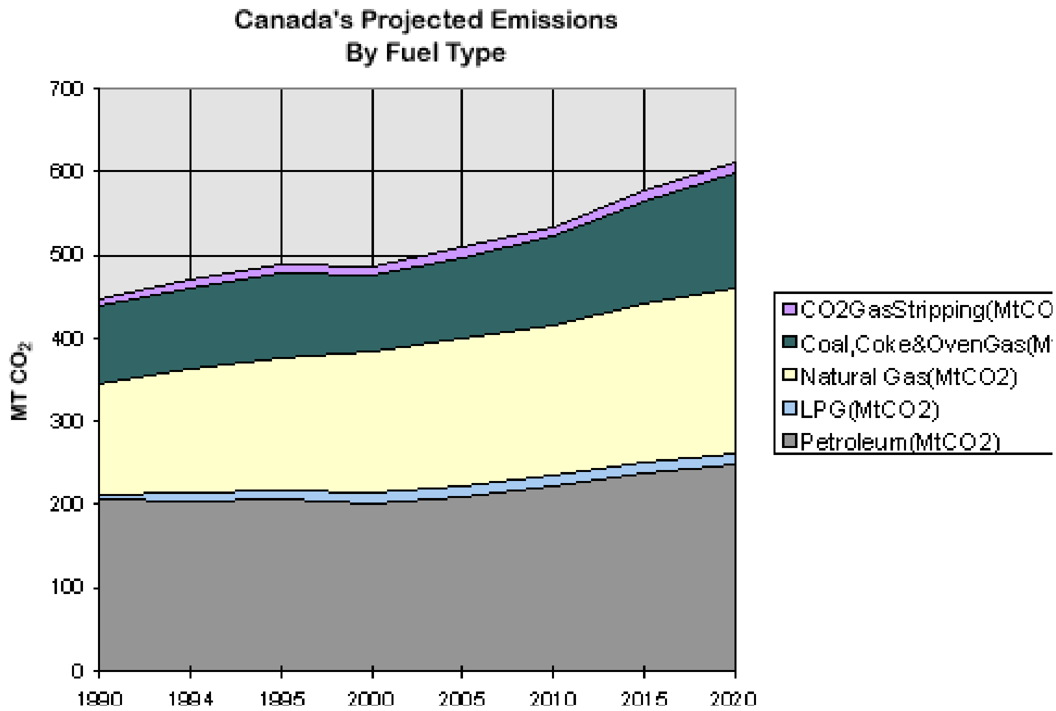


Figure 4: Historical and Future Emissions from the Use of Carbon Fuels

Nuclear, Hydrogen And Renewable Energy Sources

It appears that nuclear and other renewable energy sources and hydrogen are uniquely synergistic in reducing potential costs, electricity generation emissions and end-use transportation emissions. This potential synergism is largely unexplored today, because of historical use patterns and the competing self-interests among the various proponents. The potential needs to be exploited as a bridge towards tomorrow.

Nuclear energy is currently in a paradoxical situation. Although it is a technology which has produced large reductions in GHG emissions in Canada and the world, nuclear energy is relegated in the emissions debate either to be ignored or dismissed. Yet it is athe only non-carbon source whose increased use is capable of replacing carbon (coal, oil and gas) sources. The pure renewables will gradually grow within the energy mix but without additional nuclear capacity, it will be impossible even to hold greenhouse gas emissions near current values without enormous economic disruption. Nuclear electric is the largest *proven* non-carbon emitting sources in the world today. Yet the reports cited above (Berry,1996; Suzuki Foundation and Pembina Institute, 1998) and other reports (NRCan,1998; USDOE,1998) do not include significant non-carbon nuclear energy in the future energy scenarios or emissions-reduction measures. In the Suzuki Foundation and Pembina Institute, (1998) report, large claims are made for as yet unproven measures and increased taxation and legislative measures to protect the environment, yet the word nuclear appears nowhere as a "Canadian Solution" nor is it considered or admitted to be "green". Where given, the reasons for this omission are usually vague grounds of safety, waste disposal or economics. On examination, the objections are unsupported by facts but related more to the exploitation of fears and misperceptions.

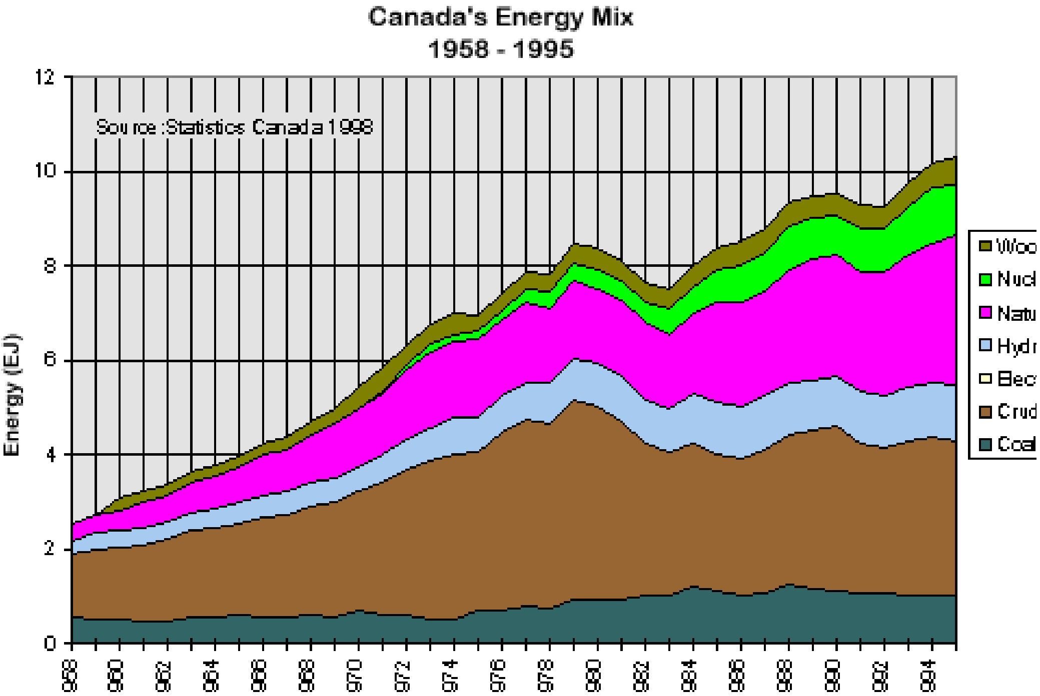
Compromise is impossible with those whose only agenda is the cessation (absolute and entire) of nuclear power, and in whose estimates and visions of the future nuclear power does not figure or appear at all. To many, nuclear power lives in the shadow of nuclear weapons, and is unacceptable on those grounds alone. This view prevails, despite nuclear power providing some 17% in 1995 of the entire world's electricity generation and some 7% of total energy consumption.

Preservation of our environment is in all our interests, and the needs of the environment must be balanced with the needs of all people and societies to grow and prosper. We must be *inclusive* in our selection and use of energy technology, *not* exclusive; we will need all energy sources, working together, that are economically viable.

The effects of nuclear power on future emissions reductions are estimated to be upwards of ~50 Mt/CO_2 per year in Canada alone (Pendergast et al, 1998); but there are no plans to take wide spread advantage of this. Such plans exist in France and Japan, though not in the United States or Germany. In the latter group of countries, natural-gas plants with reduced capital costs are seen as the alternate power sources. In a "competitive" power market, with no penalties or taxes for carbon emissions, gas turbines from IPP's will be selected as long as natural-gas prices remain at today's levels. In the United Kingdom, this has led to a drastic reduction in coal-burning and what one might reasonably regard as excessive reliance on gas-powered generation.

With respect to safety, the record of the nuclear industry has been and continues to be excellent, as measured by any conventional or relative measure, and personal risk is extremely low. The perception of nuclear safety is dominated in many people's minds by the Chernobyl accident spreading radioactivity over Russia and the Ukraine and wider areas. This accident was for an uncontained plant design, where the standards of safety in design and operation did not match those of other countries when adopted for power generation. The risk of a large accident in a modern western reactor is quite remote, and the chance of any large release highly improbable. On waste storage, as shown by the recent protracted Canadian review, and the studies in Norway, the United States and the United Kingdom, the issue is technically solvable, using deep storage in secure containers. Implementation is embroiled in a continuing socio-political discussion on siting and future generation risks. In fact, nuclear energy waste satisfies a "sustainable criterion" for energy sources because the waste decays naturally to the level of the original uranium after 300 to 400 years, leaving little more than a geological curiosity. Nuclear fission and fusion reactions occur continuously and renewably in nature, both in the centre of the earth, in the sun, and the cosmos. On cost and relative economics, the generating costs for nuclear energy continue to be competitive with all other sources, even despite the current short-term glut of relatively cheap oil and gas, and the inclusion of the total life-cycle costs of decommissioning and waste disposal.

Hydrogen is also a paradoxical situation. As a carbon-free energy source, it is widely accepted as "green". However, it is currently produced by the use of processes that consume carbon-based fuels with co-production and the almost invariable emission of CO_2. The total cycle, therefore, cannot claim significant emissions reductions unless the production process becomes carbon-free. Indeed, the inefficiencies introduced by production, distribution, and end-use of hydrogen may increase overall emissions. For historical reasons, the societal and industrial infrastructure is based on carbon fuels (see Figures 4 and 5). Safety perceptions are driven by images of the uncontrolled burning of the large air ships or exploding tankers. In reality, modern safety standards are entirely adequate. The use of hydrogen in large rocket propulsion is an everyday occurrence; natural-gas is already accepted without question, despite its flammability and explosive hazards. Hydrogen is largely ignored as a potential energy source when emissions reductions are needed. Off-peak electricity, or renewable (electricity-producing) energy sources are often stated to be the appropriate source of the energy needed to produce hydrogen (Berry,1996) using wind farms and solar photo-voltaics, though the economic viability of hydrogen production by electrolysis would be significantly weakened by poor capacity factors. As shown in Figure 6, for the future the comparative cost of the renewable sources is significantly above current competitive market prices (without incentives). If hydrogen supply were to be based on renewable sources such as wind or solar, the principal use of hydrogen in transportation end-use would be then delayed further, even before considering that it would be competing with existing transportation infrastructure.


Canada's Energy Mix
1958 - 1995

Source :Statistics Canada 1998

Figure 5: Canada’s Historical Sources of Energy

Finally, renewable energy sources are also in a paradoxical situation. Wind and solar are distributed and intermittent sources of power that require interconnection to alternative secure sources (a grid). The large grid is synergistic because it can provide access to an energy "bank" (i.e., pumped storage or displaced hydro generation) for the electricity generated when it is not immediately needed. Net metering and credits for local generation capacity can be established by means of the grid. Thus although local generation costs may have decreased, the total system cost tends to be higher because storage facilities or backup generation facilities are needed. Limits on the extent of reverse metering by power size to exclude gas turbines (Suzuki Foundation and the Pembina Institute, 1998), also inadvertently exclude large wind farms that must have a (grid) reserve capacity because of the relatively small (~40%) wind farm capacity factor.

Many mechanisms are being introduced to encourage investment in embedded renewable power sources. Hence the concept of "green" quotas - as in Denmark and United Kingdom, or Portfolios, or Capacity Credits - is being legislated as a fraction of the electricity market as an encouragement to help mask or defray the cost. In the United Kingdom, a fossil-fuel levy has been used to support the decommissioning of old nuclear plants and the development of renewable generation, which led to about ~300 MW(e) of wind power. The "level playing field" needed for renewables to compete in the short term must be tilted in their favour. Carbon or emissions taxes - which would encourage greater wind power and solar penetration - also favour nuclear energy and, in part, natural-gas. Competitive power markets favour gas burning and nuclear base-load plants as a relatively cheap and existing measure. But renewables should not have to compete directly with nuclear plants because the perceived and actual end-uses of the electricity generated are totally different and synergistic. Thus, nuclear and some hydro power sources supply a base load and robust grid for large-scale domestic and industrial purposes. Renewable sources provide intermittent power, not necessarily coincident with peaks, load cycling, and local consumption. It will take many decades for renewables to penetrate the energy market significantly (BWEA, 1996) because of the shear scale of the enterprise and the existing need.

Thus to have significant market penetration, wind and solar renewables today must have preferred market share, more cost, significant backup and - most of all - time to develop. Even so, they cannot provide the major share of the energy needed even by the most optimistic proponents (BWEA, 1996) and are also vulnerable to competitive market forces and natural-gas burning.

In Figure 6, we compare estimates and trends for future generating costs from many alternate sources. These values are derived directly from The European Renewables Energy Study (TERES, 1997) and from current actual CANDU values without allowing for any future nuclear cost reduction. Thus the nuclear estimates are for existing (today’s) designs, without assuming any technology enhancements; the renewable estimates assume significant improvements. The European data we use here are of interest because there is already significant wind-energy deployment and experimentation with "competitive" but regulated energy markets, and on market share targets and subsidies for wind farms. Regardless of the absolute magnitudes, which show significant cost increases when adopting renewable sources, the relative estimates in Figure 6 also clearly show that 20 to 30 years are needed for renewable energy costs to significantly decline.

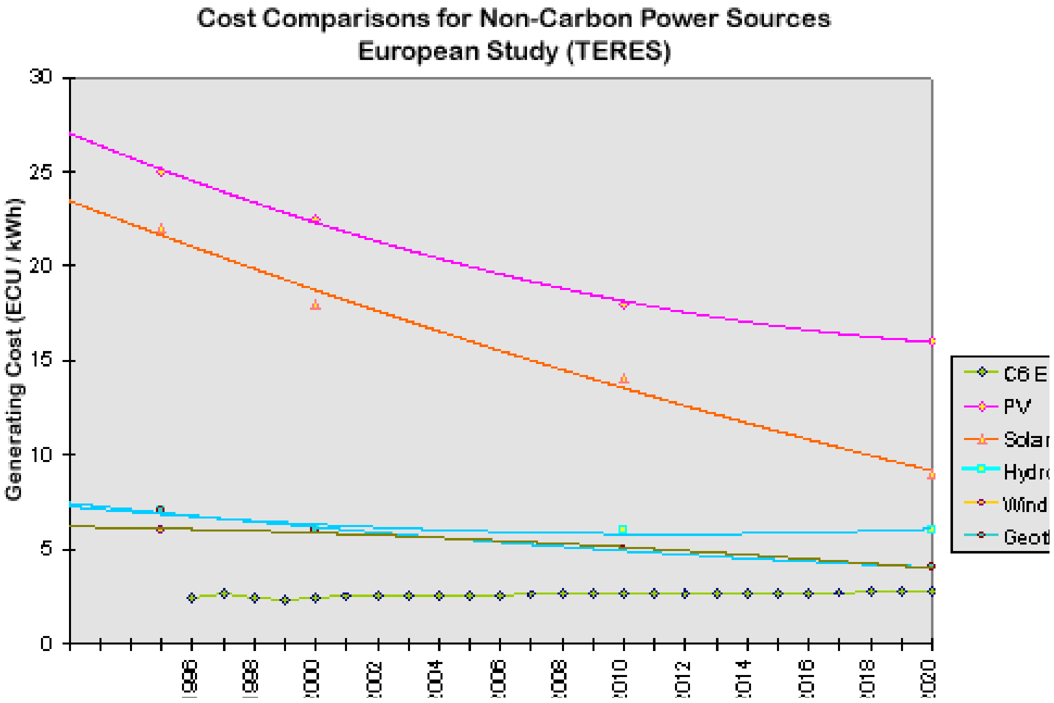


Figure 6: Comparative Current and Projected Electrical Generation Costs

The non-carbon bridge to the future, proposed here, is a balance of hydrogen, renewables and nuclear energy sources, coupled with a management of emissions. The portfolio of electric energy sources is robust in the sense that nuclear is available to back up solar and wind energy, and hydrogen serves as an energy storage medium. The policy measures adopted (which are code words for legislation and taxes) must be implemented in a manner that will not disrupt the economy. It took nearly the whole century to build up the present electrical generating capacity and energy-use patterns: it is an immense enterprise, and it is unreasonable to expect all this to be changed quickly. The present paper argues that a bridge be built to enable changes to occur more naturally over the next 20 to 50 years, without significant economic disruption.

The Nuclear Source Of Hydrogen

As shown in Figure 7, energy use in transportation is about 1.5 EJ/y and is rising. Electricity generation in Canada uses about 3 EJ/y and is also rising, and nuclear electricity generation is currently about 15% of total capacity. Sources of hydrogen usually considered are steam methane reforming, decomposition by partial oxidation or electrolysis.

NRCan (1998) estimates that energy end-use in Canada will grow considerably over the next 20 years, even though the assumed economic growth rate is only 1% ~ 2% per annum. The transportation and industrial sectors show the largest estimated increase.

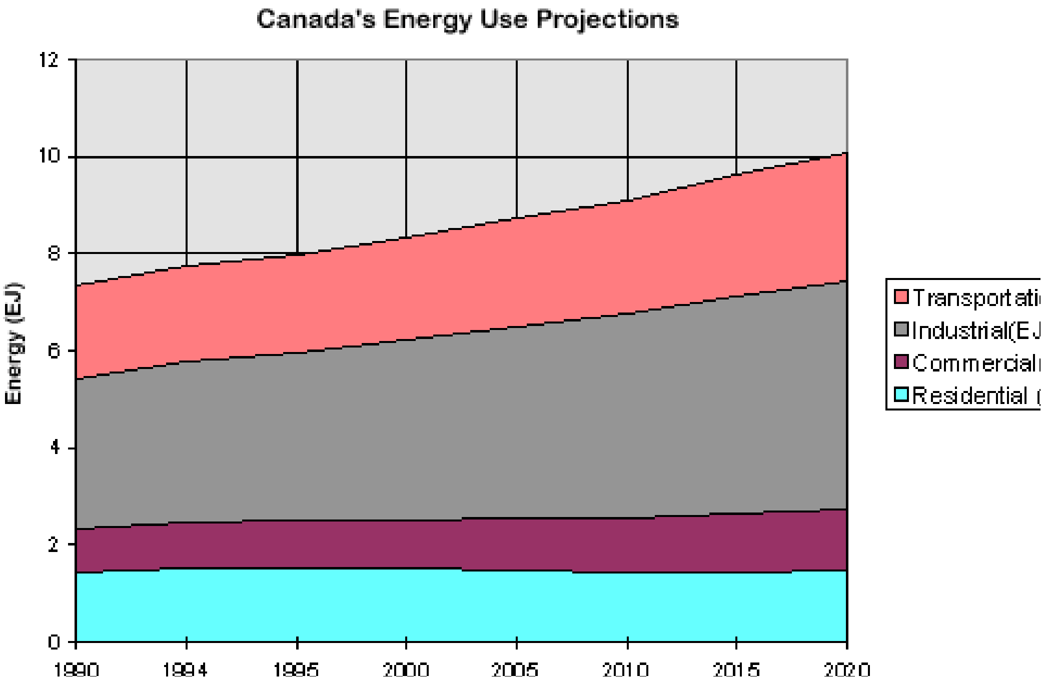


Figure 7: The Present and Projected Use of Energy in Canada

Hydrogen could provide a significant part of this expanding demand provided it does so in a way that minimizes GHG emissions from the H_2 manufacturing. To do so, the production would have to come from non-carbon electricity generation (namely a CANDU reactor). To be efficient in energy production, the reactor uses heavy water (D_2O) as its moderator.

Thus the basic and simple concept is that the reactor is used to generate electricity for the grid, for local or distributed hydrogen production. By-products include heavy water, oxygen and process heat. Where hydrogen production is centralized, nature's providence allows for the very economical production of heavy water during electrolysis of water into hydrogen and oxygen. Heavy water (D_2O) is an essential and expensive moderator and coolant component of CANDU reactors. There is, thus, a very substantial additional economic synergy, which significantly reduces capital costs of the CANDU reactor, embedded in the application of nuclear energy to hydrogen production.

Such a reactor design is available as the CANDU 6, which is exported and is also operating in Quebec and New Brunswick. A larger design - the CANDU 9, which is derived from the Bruce and Darlington plants - is also available. In total, 22 CANDU plants are operating successfully in both Canada and in several other countries (namely Romania, Argentina, Korea). The lifetime average capacity factor is ~65%, and is about 85% for the CANDU 6 designs. Canada is one of the largest exporters of such technology in the world and competes successfully against fossil, gas, and other nuclear generation designs.

With respect to GHG emissions, as shown in Figure 8, CANDU reactors have reduced emissions in Canada by over 1000 Mt/CO_2 to date, and continue to avoid emissions by about ~100 Mt/y. Together with hydro power, these represent an essentially zero source of CO_2.

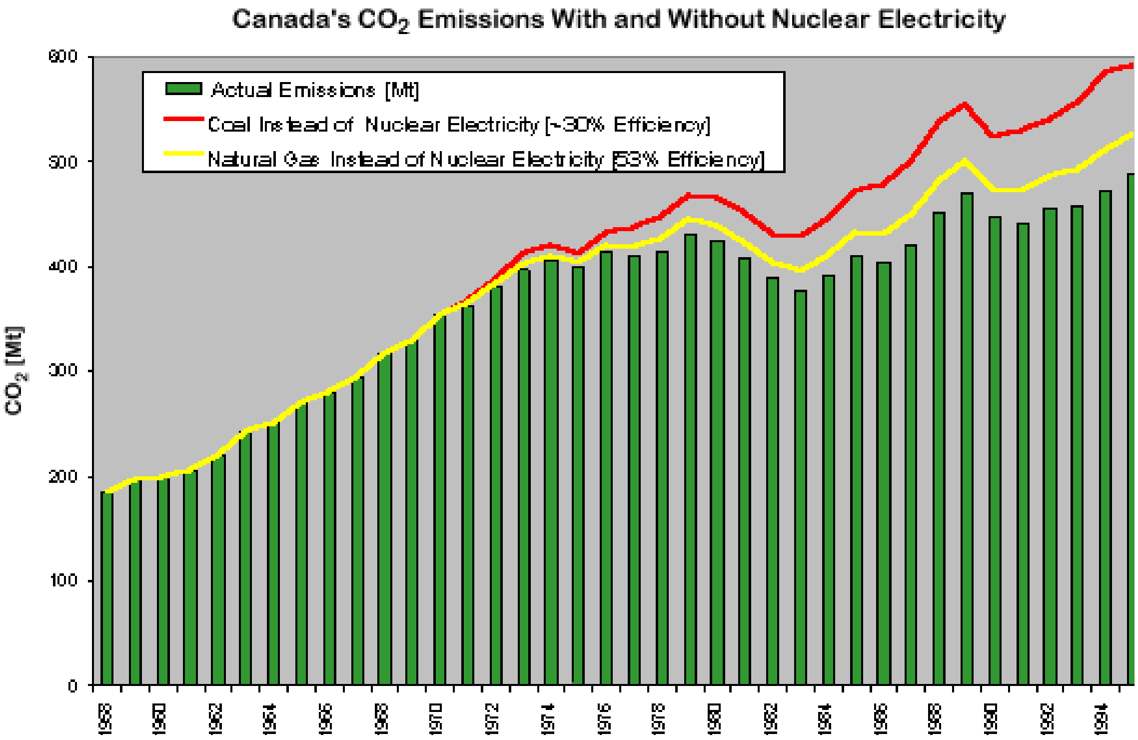


Figure 8: Avoided CO_2 Emissions from Nuclear Energy Use in Canada

Projections show that a fleet of 22 CANDU reactors installed by circa 2020 would meet, with hydro power, all of Canada's estimated needs for electricity and could reduce CO_2 emissions by a further 50 Mt/y compared to the most efficient gas-turbine generation. There is no negative economic effect because this additional power generation is needed to grow the economy anyway, according to the NRCan 2020 projections.

In fact, the effect on construction, technology and engineering exports would be positive. Without such measures, electricity generation in Canada is predicted to fall, relative to the gross domestic product (GDP) (NRCan, 1998). The drop relative to GDP signifies that relative industrial decline will occur and that the net use of electrical energy in Canada will be reduced (probably resulting in significant price changes for energy).

Hydrogen Generation And End-Use Alternatives

a. Central Hydrogen Generation

One non-carbon concept is to generate hydrogen using a central plant to take advantage of the economies of scale. Hydrogen can then be distributed by tanker or pipeline either as a compressed gas or in a chemically combined form such as ammonia to the local distribution sites (truly gas stations) for final distribution and use. Hydrogen produced in this manner is sensitive to the assumed cost of bulk electricity, which is typically about 25 to 33% of the total H_2 cost.

For essentially zero emissions, the preferred and simplest hydrogen production process is electrolysis of water. The costs have been carefully analyzed and show that hydrogen can be produced economically in advanced electrolytic equipment at about 70% efficiency, so that the energy required is order ~50 kWh(e)/kg H_2. By-product, D_2O, can also be produced using about 50 kWh(e)/kg considering the efficiency and losses in the process.

Using an existing reactor design, it is possible to achieve an 80% operating capacity factor, as has been proven for the CANDU 6 plants. Calculations for a commercial-scale electrolysis plant show that a 690 MW CANDU 6 reactor can also simultaneously co-generate about 95 t/y of D_2O at that capacity factor. Four or five years of the plants heavy-water production will fill a CANDU system. Since annual consumption resulting from leakage is very small, the system is thus more than self-sufficient in heavy-water production. After 6 or 7 years of production, a plant would provide sufficient heavy water to supply about 4 more similar plants. Thus we have, for each year:

One CANDU reactor @ 690 MW(e)=>95 t/y D_2O + 97 kt/y H_2.

At today’s prices, and to give perspective on the order of magnitude, the hydrogen is valued at about $800/t, using electricity generated at ~2.5 cents/kWh(e), and is hence potentially worth ~$75 M/y revenue at the wholesale site. The D_2O by-product is worth about another ~$25 M/y at an assumed market price of $250/kg, giving a total potential revenue or avoided D_2O cost of ~$100 M/y.

b. Embedded Hydrogen Generation

Distributed sources are another option, and local small-scale electrolysis has been examined because, in addition to not needing a central facility, local generation avoids transportation costs and large storage containers (Berry, 1996). But electricity supply is still needed, and this need can be derived either from a large grid with central power plants, or from local renewable (wind) power.

It would seem highly desirable to have a local small-scale capability for H_2 manufacture. The extra cost of compression locally is also small, say, 10% of the generating cost. As will be seen, the local generation need is quite small. Ideally hydrogen would be generated during off-peak periods of the electricity supply system, thereby better utilizing electrical generating capacity. The pricing structure for electricity could be designed to encourage off-peak use**.**

Synergism With Hydrogen In Transportation

At present electricity represents a negligible ~0.2% of fuel consumption in transportation, which is the unchallenged domain of oil and gas. Transportation in Canada alone represents some 15% of the GDP, with a total energy use ~1.5 E/J/y causing emissions of about 150 Mt CO_2/y, which are projected to rise, as gasoline use rises, to about 200 Mt CO_2/y by 2020 (see Figure 9). Canada's fleet of personal vehicles consisted of about 15.5 million cars and light trucks in 1995 (NRCan, 1998). These vehicles alone generated 91 Mt of GHGs expressed as CO_2 equivalent in 1995.

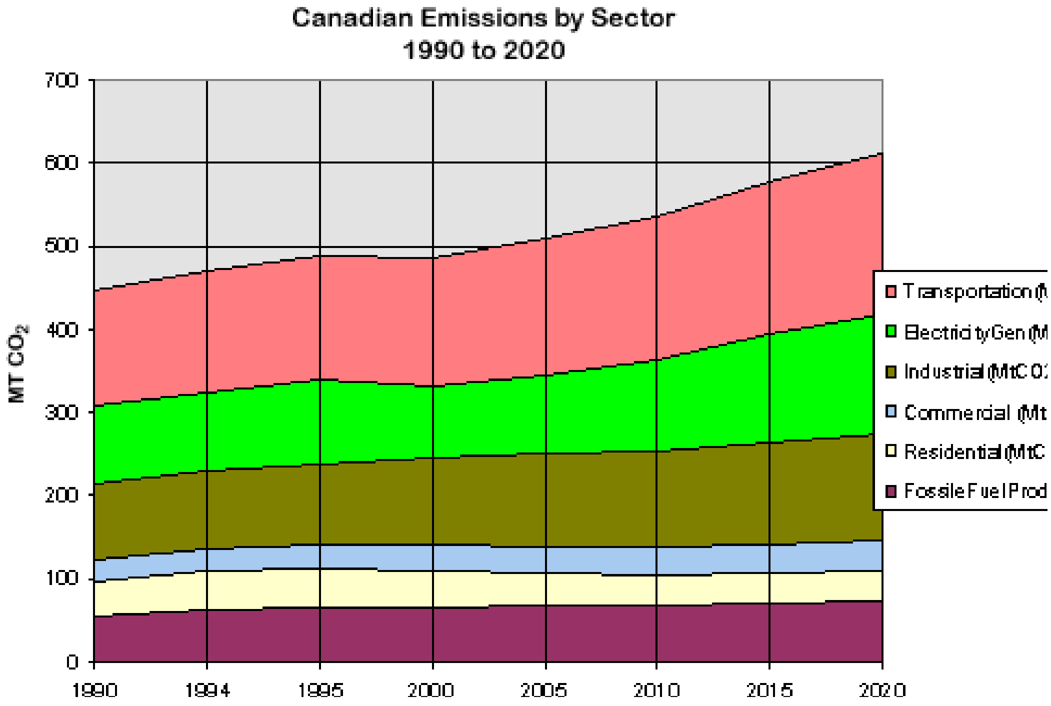


Figure 9: CO_2 Emissions Projections by End-Use Sector

The transportation emissions exceed those that are due to electricity production because of the latter's large use of non-carbon power sources. Clearly, help to reduce transportation emissions is needed but without disrupting the infrastructure and the manufacturing capability and its large investment. Refinements to engines, roads, and vehicle design will all help but are unlikely to make gains above the order of ~10 Mt CO_2/y: the greatest potential reduction is derived from fuel switching.

Extensive analysis has been undertaken on the costs and benefits of hydrogen as a transportation fuel (Berry,1996) which we do not need to repeat. In principle, it is very attractive and simple. Hydrogen is abundant, and it can be burnt either as a raw gas or by a carrier, or it can be used to feed mobile on-board fuel cells to recombine with oxygen and produce water and energy. The actual vehicle adopted can be from a variety of combinations or choices, e.g., of an internal combustion engine (ICE) fed by methanol, natural-gas or hydrogen, combined with batteries, fuel cells or conventional combustion or both.

Now for hydrogen production, as for everything else, we must consider the entire process from production to end-use, so the carbon dioxide emissions using conventional reforming and electrolysis based on fossil-fuel sources are comparable or even greater than those from simply using gasoline (see Figure 10). Thus there is, significantly, no real advantage to using H_2 to reduce emissions, and one might as well burn natural-gas or propane.

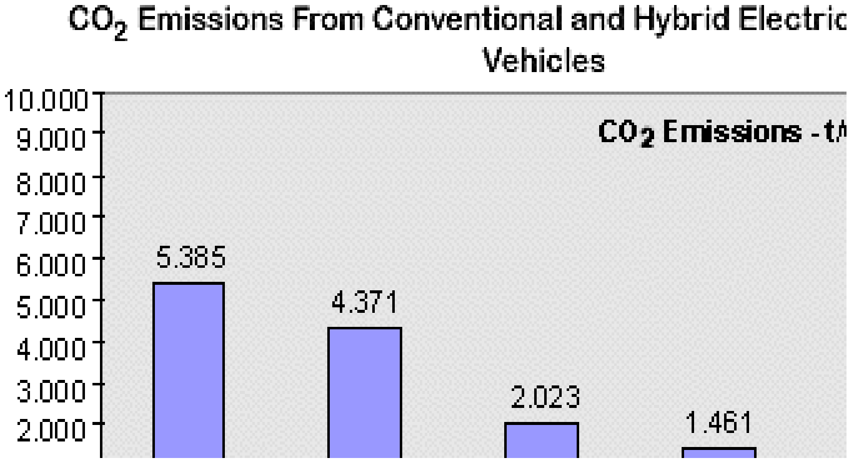


Figure 10: Relative Transportation Emissions from Improved Fuels

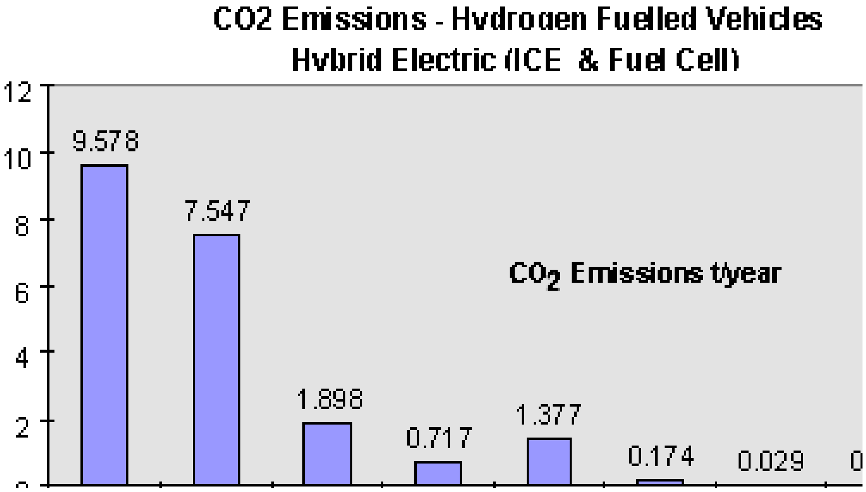


Figure 11: Effect of Non-carbon Sources on Hydrogen Production

The lowest carbon-dioxide-emitting vehicles are the hybrid and fuel cell vehicles. The achievable efficiency of the process is about 50% at the vehicle level (going from combustion to motion). This efficiency immediately gives about a factor of three improvement in the ‘equivalent’ fuel economy to order 80 to 90 miles per gallon (~2.75 l/100 km).

An Illustrative Canadian Example

From the preceding analysis, there arises an opportunity for a real and distinctive Canadian technological solution to increasing emissions in power generation and transportation. As the basis for this illustrative example, we take the energy, economic and emissions projections published by the Canadian Government (NRCan, 1998) and estimate the potential maximum impact of significant hydrogen-fuelled vehicles on the future.

Consider an average Canadian vehicle, V, driven each day about 57 km/D/V (~21 000 km/y) needing about 0.4 kgH_2/d/V for an equivalent 90 mpg. Thus, as we have seen, one 690 MW(e) CANDU 6 operating at 80% load factor can supply ~660 000 V/d with H_2 fuel with no net increase in CO_2 emissions. So we have

One CANDU @ 690 MW(e)=>95 t/y D_2O + 660 000 H_2 V/d.

Therefore, a program of 20 CANDU reactors would supply ~13 M hydrogen vehicles, and would be self-sufficient in D_2O production, and could supply excess D_2O for export. It is likely that fewer than 20 additional CANDU reactors would suffice, as it is likely that off-peak power from the base electrical fleet could be utilized to produce hydrogen. The fuel cell, electrolysis, reactor, and vehicle technology would also be exportable.

As shown in Figure 12, we can simply estimate the potential maximum reductions in Transportation emissions from the present vehicle technological base (petroleum fuels), where we have kept the aviation and rail contributions to transportation unaltered, although those would be every bit as amenable to evolution toward hydrogen fuel. The maximum reduction by 2030 is ~90 Mt CO_2/y, and would still be ~30 Mt CO_2/y even if a wholesale switch to higher efficiency and alternate-fuelled vehicles were also achieved.

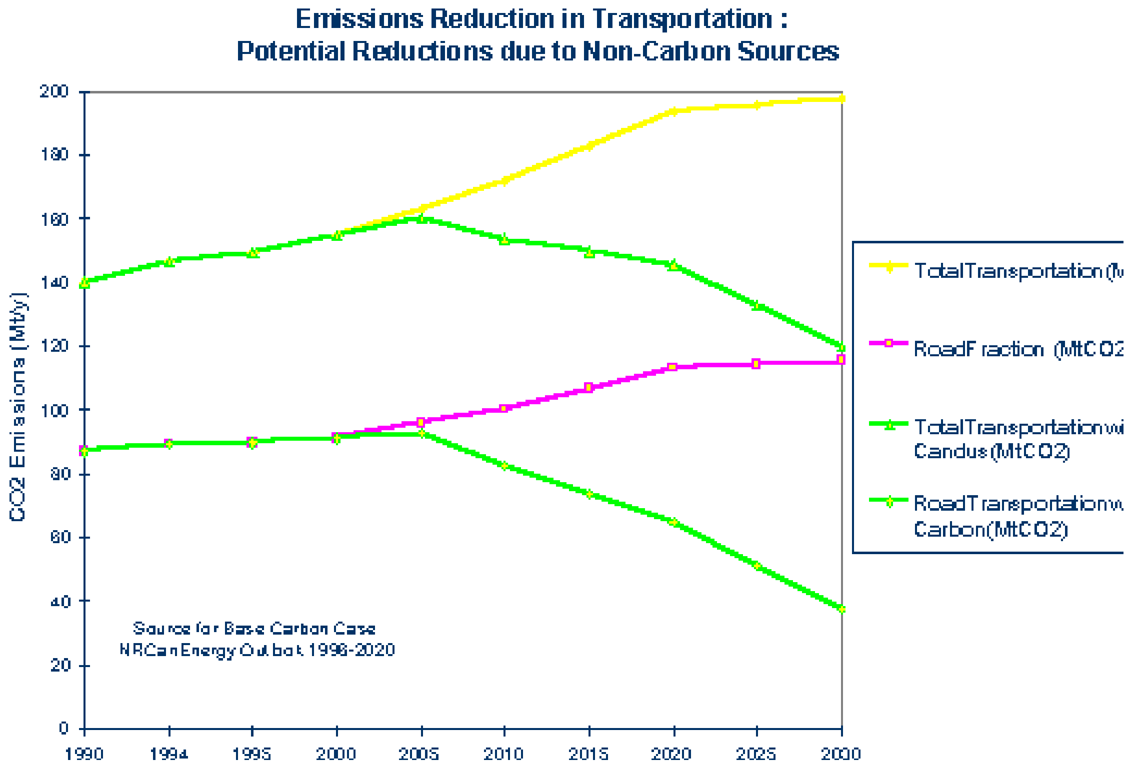


Figure 12: The Maximum Potential Effect of H_2-Fuelled Vehicles

In this simplified scenario, the rate of use of H_2 in transportation, assuming the availability of fuel cell technology, is governed by the rate of introduction of CANDU reactors. A sensible build-rate is at about one per year, which corresponds as we have seen to ~650 000 H_2 V/y, which is about 4% of the vehicle population per year starting in about 2005, and proceeding to a fleet of about 13 M H_2 vehicles by 2025.

Up to and beyond that point, at a contribution level of around 10% of the fleet, distributed electrolysis could be introduced using renewable electric supplies (primarily wind power). The required renewable content would then be of order ~1500 MW(e), which corresponds to about 300 distributed farms, which requires a build-rate of the order 10 5 MW-sized farms per year. In context, this is of the order 5 times the present installed UK wind farm capacity introduced over about 10 years.

The traditional measure of energy and electrical usage efficiency in the economy is the ratio of GDP to electricity ($GDP/kWh(e)). This ratio is maintained at its historical low value, of order $1.2/kWh(e), so there is no economic change. The revised apportioning of the forward emissions by sector then would be as shown in Figure 13:

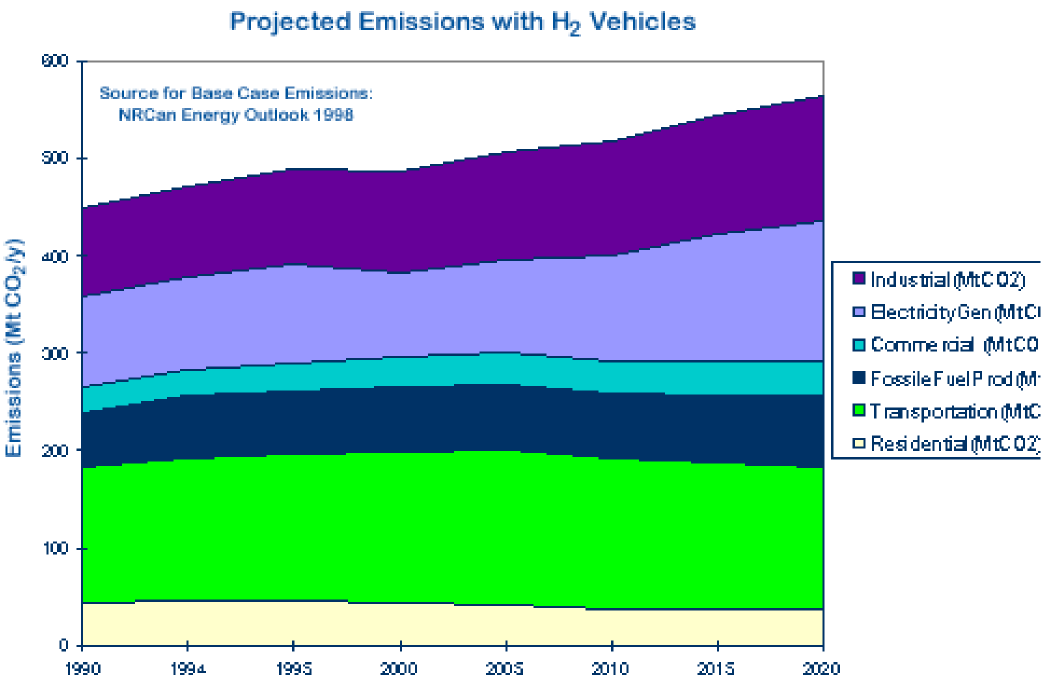


Figure 13: Hydrogen Vehicles and Projected Emissions

The impact of a significant reduction of emissions because of additional nuclear electricity generation can also be included, as would be needed to meet, for example, the Kyoto Accord goals. In this case, we find that the adding together of the hydrogen utilization in transportation and nuclear energy in electrification provides a leveling of the total CO_2 emissions rate (see Figure 14). Given other voluntary and efficiency measures, there is clearly a fair chance of stabilizing emissions at values near to today’s values. We note that this stabilization is achieved without affecting industrial energy use, which was one of the goals of this example.

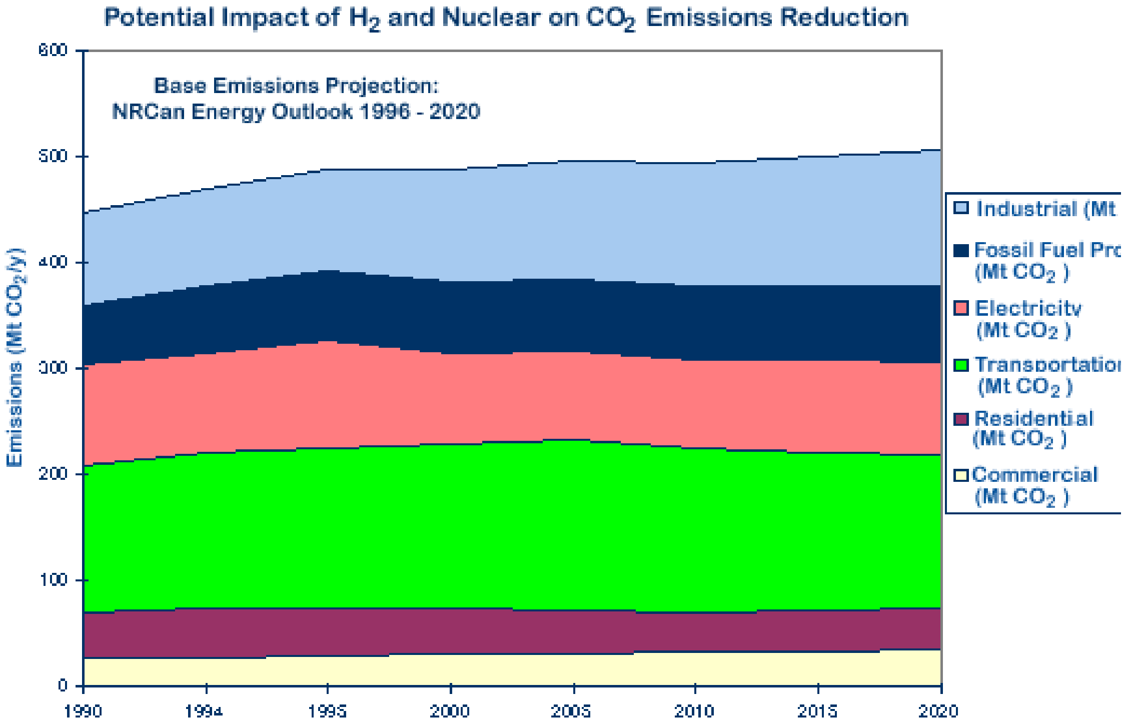


Figure 14: Potential Impact of Hydrogen and Nuclear Energy on Emissions

With 20 CANDU reactors producing electricity for industry, and as many as 20 more dedicated to transportation, the avoided CO_2 emissions reductions in electricity generation and transportation are ~120 Mt/y. There is no need for any restrictions on the oil and gas industries, or any others because these industries continue to fuel the base industrial and residential sectors, and the transition electricity and transportation requirements until at least 2020 to 2030. In context, this size of fleet is comparable to the present Canadian CANDU capacity.

Funding The Investment Internally: The Cost Benefit

The hypothetical zero emissions for transportation, and reduced emissions growth overall is theoretical but is based on existing technological concepts. Both the electricity generation needed and the hydrogen transportation can be designed and deployed, but at a cost. As of today, carbon dioxide emissions are freely allowed. Suggestions and approaches include taxes, credits and emissions trading, all of which potentially negatively impact high-emitting nations and their economies. But we can use the concept for internal costing and cost-benefit purposes. We explore that concept to see whether hydrogen transportation coupled with non-carbon power generation is indeed internally cost-effective.

Current average Canadian light vehicle carbon dioxide emissions are ~5.3 t CO_2/V/y. We assume the avoided emissions attributable to nuclear and hydrogen energy are ~3 Mt CO_2/y per CANDU reactor, based on existing vehicle technology. With no additional taxes on hydrogen as a fuel, as for existing propane and methanol fuels, the operating savings to the consumer are the difference in the gasoline and hydrogen fuel charge costs. The costs for the hybrid vehicle are also greater, so we give some illustrative and comparative examples.

The average Canadian car is driven 21,000 km/year and generates on average about 5.3 tonnes of CO_2 per year. That translates to abut 1.45 tonnes of carbon, or 1.72 tonnes of gasoline (based on octane C_8H_{18}) or 2400 litres of gasoline per year. At ~ 56 cents/l that costs $1344/year (of which about $500 is taxes). It is also a fuel consumption of 11.4 l/100 km.

The cost for hydrogen fuel as an alternate depends on the electricity cost, and our estimates are based on electrolysis using realistic efficiencies, amortized costs, and facility sizes. For distributed electrolysis, at the current retail rate of ~ 8 cents/kW h, the 8800 kW h it would take to run the electrolyser to generate hydrogen for a hybrid 90 mpg car would cost ~ 700 dollars/year for hydrogen, with no additional taxes. Actual fuel costs would thus be similar to a gasoline vehicle ex taxes. Using a local electrolyser costs about $2500 and lasts for, say, 5 years. The hybrid vehicle costs are uncertain but we assume about $5000/V based on advanced fuel cell technology (Berry, 1996). The costs for hydrogen per vehicle are thus about $2200/year. With a savings of about $1200 in taxes and gasoline for a net cost of $1000. Including the tax on the gasoline, of say $500, the total will be more like $1500 for 5 tonnes of CO_2 or a cost of $300/t CO_2 at the consumer level. Thus having local electricity generation for electrolysis without having to pay transmission costs, represents a significant opportunity and challenge for distributed power sources.

Alternatively, consider bulk purchase of centrally produced H_2. To assess the cost of the avoided emissions, we may again proceed by assuming gasoline at 56 c/l ($2.50/g) and hydrogen at $800/t, produced by wholesale electricity (without transmission costs) at 2 to 3 c/kW h. The cost-savings to the consumer on the emissions is ~$270/t CO_2,which is of similar order. If carbon emissions were indeed valued (by whatever trading, substitution or tax method is appropriate) this saving is in principle available to invest in hydrogen infrastructure.

The cost of the electricity and hydrogen electrolysis equipment are recovered in the electrical (and hence H_2 fuel) cost, by the hydrogen producers/suppliers, which may be Independent Hydrogen Utilities (IHUs) The remaining costs to be funded are the costs of setting up the H_2 transportation and distribution itself, and the fuel cell vehicle costs.

The infrastructure installation and penetration issue has been approached with the concept of Hydrogen Corridors, as a starting point, in high-density traffic areas, to enable a gradual start on the infrastructure.

Even at 1/5th of that price ($200/t CO_2) the cost of the increased vehicle complexity is paid for internally within the vehicle actual or depreciated life of order ten years. Tax credits for H_2 vehicles could also be considered as is already done for other start-up situations.

Given that the funding is within the country, there is no external (emissions trading) cost, and the capitalization for the start of a new industry is funded. The alternative of trading carbon or emissions credits to or with other countries does not allow that flexibility for internal investment of the proceeds with any internal emissions savings.

The net cost benefit to the country of investing in non-carbon zero emissions H_2 fuelled transportation systems is of order 120 Mt CO_2/y times the (cost of CO_2 in $/t) per year, thus totaling a benefit of order $10 to 100 B/y less the minor tax losses, which also stimulate the economy. The increased vehicle costs are of order $3 B/y, which is relatively small, and shows a superficial benefit to cost ratio of order 3 to 30 for the consumer that is entirely reasonable. However, as in any major decision, significant capital investment must be made in vehicle manufacturing, hydrogen production, and nuclear power facilities.

But as pointed out by Scott (1994-1998), the H_2 currency will only be accepted and used if it is efficient and attractive, all other factors being equal. The designation of H_2 use in transportation as ‘green’ is vital to that end, and can be endorsed only if it is matched with non-carbon H_2 generation power sources, such as nuclear energy and renewables.

Conclusions

A uniquely synergistic opportunity between hydrogen, nuclear and renewable non-carbon sources of energy has emerged. This opportunity arises because it is necessary to reduce emissions without harming the economy and industry. A zero-emissions model for the total process is explored by using H_2 as a fuel in transportation. To achieve the emissions reduction, a non-carbon power source must also be used.

The ability to synergistically create a market for hydrogen, fuel cells, reactors, and renewables - together with the export potential - is presented and must be considered further as a significant national business opportunity.

The H_2 is derived by large-scale electrolysis, at competitive costs. Generators or suppliers, which may be Independent Hydrogen Utilities, would use the non-carbon CANDU reactor to provide the needed power and as a by-product heavy water for further plants, and excess power for exportation, as is the entire technology.

In Canada, the introduction of H_2-fuelled vehicles over the next twenty or so years could lead to avoided CO_2 emissions of order 120 Mt/y in the electricity generation and transportation sectors. This option is without additional taxes, mandates, or policy measures to restrict industrial or residential energy use. Thus the planned additional voluntary measures would suffice.

A national program would require of order 20 CANDU reactors producing the H_2 and D_2O by electrolysis, some 300 wind farms, and about 650 000 H_2 fuel cell vehicles produced per year up to a total of about 13 M vehicles by 2030. Nuclear energy should be regarded as an enabling technology, for H_2 fuel introduction, CO_2 emissions reduction, and renewables support.

The increased costs are in the vehicle equipment and the hydrogen infrastructure, the fuel costs being reclaimed by revenue by the hydrogen producers and equipment suppliers.

A cost-benefit argument can only be constructed based on avoided emissions, the lack of additional mandates, restrictions and legislation, and less potential and onerous restrictions on the industrial end-use and the energy-producing sectors.

The preceding analysis is simply one important example of how synergistic opportunities may be explored, and of innovative future approaches to electrical energy production and end-use that leverage existing and future Canadian technological capabilities.

References

Berry, G.D.,1996, "Hydrogen as a Transportation Fuel: Costs and Benefits", Report UCRL-ID-123456, Lawrence Livermore National Laboratory, USA.

BWEA (British Wind Energy Association), 1996, "Wind Energy: Power for a Sustainable Future", London, England.

Imperial Oil, 1998, " The High Costs of Kyoto", Ottawa, Canada.

NRCan (Natural Resources Canada), 1998, "Energy Outlook", Ottawa, Canada.

Pendergast, D.R., Duffey, R.B. and Tregunno, D.,1998, "Canada’s Nuclear Industry, Greenhouse Gas Emissions, and the Kyoto Protocol", Proc. 19th Annual Conference, CNS, Volume 1, Toronto, Canada.

Scott, D,1994-1996 , "Smelling Land"’, A Compendium of papers published in the International J. Hydrogen Energy, Great Britain.

Suzuki Foundation and the Pembina Institute, 1998, "Canadian Solutions: Practical and Affordable Steps to Fight Climate Change", Canada.

TERES II, 1997, "The European Renewable Energy Study II", CEC, Brussels, Belgium (quoted in "Guide to UK Renewable Energy Companies 1997", ETSU, Department of Trade and Industry, UK)

USDOE (Department of Energy), 1998, Energy Information Administration, "International Energy Outlook", Washington, USA.

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