How Viable is the Hydrogen Economy? The Case of Iceland

By Mamdouh G. Salameh*

Introduction

The vision of a hydrogen economy could become a reality within the next four to five decades with Iceland already leading the way to become the world's first fully-operational hydrogen economy (see Figure 1). Iceland even cherishes the dream of becoming the "Kuwait of the North", a major source of energy in a world where all nations follow Iceland's path. Icelanders even dream of exporting hydrogen and creating a booming new industry (though first they will have to figure out a way to get it there).

A hydrogen economy is a hypothetical economy in which the energy needed for transport or electricity is derived from reacting hydrogen with oxygen. While the primary purpose is to eliminate the use of fossil fuels and thus reduce carbon dioxide emissions, a secondary goal is to provide an energy carrier to replace dwindling supplies of crude oil.

The vision of a hydrogen economy in Iceland as spelled out by Professor Bragi Arnason, also known as Professor Hydrogen, is to take all of Iceland's cars and fishing trawlers and gradually replace their gas combustion engines with electric motors run on hydrogen-fuel cells just like American space shuttles. Meanwhile, harness Iceland's abundant geothermal and hydro-energy resources to begin producing hydrogen gas on a mass scale.[1]

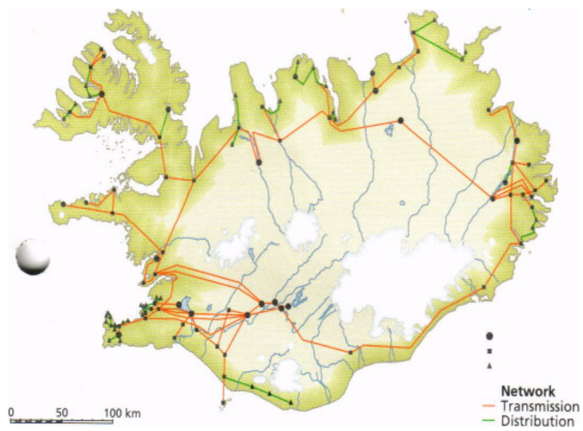

Figure 1. Iceland
Source: Energy Statistics, Iceland

Iceland is a model in the making. With a population of only 290,000 people and with its abundant hydro-energy and its huge geothermal energy, Iceland has already started the transformation into a hydrogen economy. For a number of years, public transport buses in Reykjavik, the capital, have been running on hydrogen-powered fuel cells. The next step is the introduction of hydrogen fuel cell cars for private transport. Eventually the entire Icelandic fishing fleet will be gradually powered by hydrogen fuel cells. The question is when and at what cost. Shell Hydrogen figures it would cost at least $19 bn to build hydrogen plants and stations in the United States, $1.5 bn in the UK and $6 bn in Japan compared with a few millions in Iceland.[2]

Most hydrogen on Earth is bonded to oxygen in water. Hydrogen is presently most economically produced using fossil fuels. More expensively it can also be produced via electrolysis using electricity and water, consuming approximately 50 kilowatt hours of electricity per kilogram of hydrogen produced. Nuclear power can provide the energy for hydrogen production by a variety of means but its wide-scale deployment is opposed in some Western economies while it is embraced in others. Renewable energy is being used to produce hydrogen in Denmark and Iceland.

In the context of a hydrogen economy, hydrogen is an energy storage medium, not a primary energy source. Nevertheless, controversy over the usefulness of a hydrogen economy has been confused by issues of energy sourcing, including fossil fuel use, global warming and sustainable energy generation. These are all separate issues, although the hydrogen economy impacts them all.

Proponents of a hydrogen economy suggest that hydrogen is an environmentally cleaner source of energy to end-users, particularly in transportation applications, without release of pollutants (such as particulate matter) or greenhouse gases at the point of end use. Analysts have concluded that "most of the hydrogen supply chain pathways would release significantly less carbon dioxide into the atmosphere than would gasoline used in hybrid electric vehicles" and that significant reductions in carbon dioxide emissions would be possible if carbon sequestration methods are utilized at the site of energy or hydrogen production.[3] The roster of experts who see hydrogen as the most likely replacement for oil when the wells run dry now includes the oilmen of the Bush Administration and the futurists at General Motors and Ford. Iceland's plan is now backed by DaimlerChrysler, Shell and the European Union.

Critics of a hydrogen economy argue that for the many planned applications

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See footnotes at end of text.

of hydrogen, direct distribution and use of energy in the form of electricity, or alternate means of storage such as chemical batteries, fuel cells, or production of liquid synthetic fuels from CO_2 (methanol economy), might accomplish many of the same net goals of a hydrogen economy while requiring only a fraction of the investment in new infrastructure. Hydrogen has been called the least efficient and most expensive possible replacement for gasoline. A comprehensive study of hydrogen in transportation applications has found that "there are major hurdles on the path to achieving the vision of hydrogen economy; the path will not be simple or straightforward."

One hurdle is that hydrogen fuel cells, seen as a way to provide electricity in homes as well as vehicles, rely on precious-metal catalysts like platinum. A conventional automotive fuel-cell stack contains up to 100 grams of platinum, which could cost more than $3,000 at today's prices. For the hydrogen economy to happen, the amount of platinum used in fuel cells has to come down, and soon. This will not be a problem. Car makers will be able to slash the amount of platinum needed to just 20 grams per car by the time the technology is commercialized probably in the middle of the next decade. Moreover, the platinum can be recycled. Yet the numbers still look daunting.[4]

Global car production in 2007 was just over 71 million. If only 12 million fuel-cell cars were produced a year starting the middle of the next decade and with only 20 grams of platinum per car, the quantity of platinum used will amount to 240 tonnes. This is bigger than the current annual global platinum production of 237 tonnes. At that rate the world's resources of platinum-group metals would be gone in 70 years. And this calculation makes no allowance for any growth in fuel-cell car production, or for the use of fuel cells at home. Therefore, hydrogen could only be a partial solution until an alternative to platinum is found.

Elements of the Hydrogen Economy

In the current economy, transport is fuelled primarily by crude oil refined into gasoline and diesel, and natural gas. However, the burning of these hydrocarbon fuels causes the emissions of greenhouse gases and other pollutants. Furthermore, the supply of hydrocarbon resources in the world is limited and the demand for hydrocarbon fuels is increasing, particularly in China, India and other developing countries.

In a hydrogen economy, hydrogen fuel would be manufactured from some primary energy source and used as a replacement for hydrocarbon-based fuels for transport. The hydrogen would be utilized either by direct combustion in internal combustion engines or in proton exchange membrane (PEM) fuel cells (see Figure 2).

The primary energy source can then become a stationary plant which can use renewable, nuclear or coal-fired energy sources, easing pressure on finite liquid and gas hydrocarbon resources. There is no carbon dioxide emission at the point of use. With suitable primary energy sources, greenhouse gas emissions can be reduced or eliminated. Excepting minor NOx generation from hydrogen internal combustion engines, the emissions footprint of a hydrogen economy remains that of the underlying energy generation technology.

In the 1960s NASA developed fuel cells that replaced liquid electrolytes like potassium hydroxide solution with PEMs, and the technology was applied to electrolysis too. However, the membranes were acidic, and an acidic membrane needs a platinum catalyst. What's more, the membranes themselves remain hugely expensive. Now a small British company, ITM Power, claims to have developed a membrane that can be made alkaline so nickel can replace platinum. Using half a dozen commonly available hydrocarbons, it has developed a solid but flexible polymer gel that is three times as conductive as existing PEMs. Thanks to its simplicity and the fact that it is made from readily available materials, it should also be massively cheaper. The company claims that with mass production its membrane would cost just $5 per square metre, compared to $500 for existing PEMs. As a result, ITM Power says the electrolyser would cost $164 per kilowatt of capacity, against a current average of $2,000 per kilowatt.[5] Hydrogen has a high energy density by weight. The fuel cell is

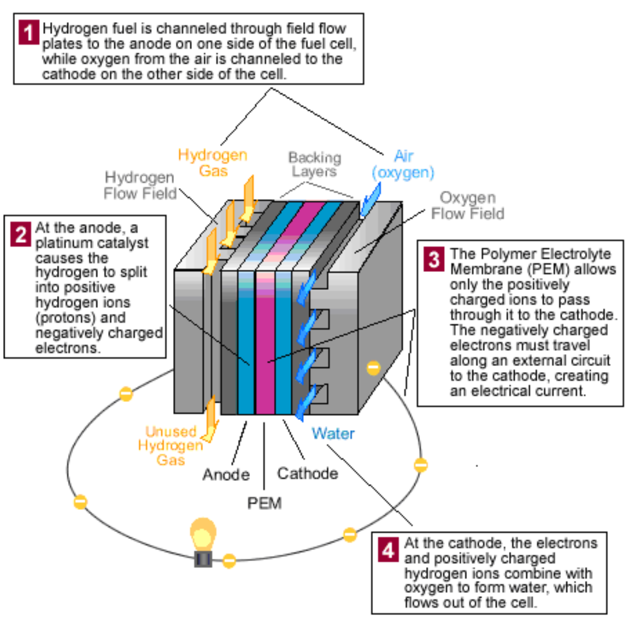

Figure 2. The Proton Exchange Membrane Fuel Cell (PEM)

Source: Courtesy of Wikipedia, the Free Encyclopedia also more efficient than an internal combustion engine (ICE). The ICE is said to be 20%-30% efficient, while the fuel cell is 35%-45% efficient (some even higher).

Current Hydrogen Market

Hydrogen production is a large and growing industry. Globally, an estimated 67 million metric tons (mmt) of hydrogen (equivalent to 4.58 million barrels a day), were produced in 2007. The growth rate is around 10% per year. Within the United States, 2007 production was about 14.64 mmt, an average power flow of 64 gigawatts. For comparison, electricity production in 2007 was estimated at 490 gigawatts. As of 2007, the economic value of all hydrogen produced worldwide was estimated at $150 bn per year.

Because both the world population and the intensive agriculture used to support it are growing, demand for ammonia is growing. The other half of current hydrogen production is used for hydrocracking, the process by which heavy crude oil resources are converted into lighter fractions suitable for use as fuels. Hydrocracking represents an even larger growth area, since rising crude oil prices encourage oil companies to extract poorer source material such as tar sands, extra heavy oil and oil shale. The economies of scale inherent in oil refining and fertilizer manufacture make possible on-site production and "captive" use. Smaller quantities of hydrogen are manufactured and delivered to end users as well.

If energy for hydrogen production were available from wind, solar or nuclear power, use of hydrogen for hydrocarbon synfuel production could expand its captive use by a factor of 5 to10. Present use of hydrogen for hydrocracking in the U.S. is roughly 4 mmt/yr. It is estimated that 38 mmt/yr of hydrogen would be sufficient to convert enough domestic coal to liquid fuels to significantly reduce U.S. dependence on foreign oil imports.

Currently, global hydrogen production is 48% from natural gas, 30% from oil, and 18% from coal; water electrolysis accounts for only 4%. The distribution of production reflects the effects of thermodynamic constraints on economic choices: of the four methods of obtaining hydrogen, partial combustion of natural gas in a natural gas combined cycle (NGCC) power plant offers the most efficient chemical pathway and the greatest off-take of usable heat energy.

One key feature of a hydrogen economy is that in mobile applications (primarily vehicular transport) energy generation and use are decoupled. The primary energy source need no longer to travel with the vehicle as it currently does with hydrocarbon fuels. Instead of tailpipes creating dispersed emissions, the energy and pollution can be generated from point sources such as large-scale centralized facilities with improved efficiency. This allows the possibility of technologies such as carbon sequestration, which are otherwise impossible for mobile applications. Alternatively small scale hydrogen stations could be used.

Methods of Production

Hydrogen is presently most economically produced using fossil fuels. More expensively it can also be produced via electrolysis using electricity and water, consuming approximately 50 kilowatt hours of electricity per kilogram of hydrogen produced. Nuclear power can provide the energy for hydrogen production, but its wide-scale deployment is opposed in some Western economies while it is embraced in others. Renewable energy is being used to produce hydrogen in Denmark and Iceland.

Different production methods have differing associated investment and marginal costs. The energy and feedstock could originate from a multitude of sources, i.e., natural gas, nuclear, solar, wind, biomass, coal, other fossil fuels and geothermal. Some facts and figures are shown in Table 1.

Energy Sources	Annual production of Hydrogen (mmt)	Investment Required	Cost per Gallon of Gasoline Equivalent (GGE)
Natural gas	150	$1000 bn	$3.0/GGE
Nuclear	provides energy for electrolysis	$ 840 bn	$2.5/GGE
Solar	provides energy for electrolysis	$ 22000 bn	$9.5/GGE
Wind	provides energy for electolysis	$ 3000 bn	$3.0/GGE
Coal	provides energy for electrolysis	$ 500 bn	$1.0/GGE
Biomass	provides energy for electrolysis	$ 565 bn	$1.9/GGE

Table 1
Different Production Methods, Investment & Marginal Costs

Source: *Popular Mechanics* Magazine, November 2006.

While hydrogen (the element) is abundant on earth, manufacturing hydrogen does require the consumption of a hydrogen carrier such as a fossil fuel or water. The former consumes the fossil resource and produces carbon dioxide, but often requires no further energy input beyond the fossil fuel. Decomposing water requires electrical or heat input, generated from some primary energy sources (fossil fuel, nuclear power or renewable energy). The economic and environmental impact of any implementation of a future economy will largely be determined by future energy development.

For the hydrogen economy to happen, industry must also come up with clean ways of producing it. Most hydrogen is currently made in refineries by heating natural gas with steam in the presence of a catalyst, but this usually relies on energy from fossil fuels and can generate carbon dioxide as a by-product. Because of this, the climate benefits of fuel-cell vehicles are scarcely better than those of petrol hybrids according to a 2003 study led by Malcolm Weiss at the Massachusetts Institute of Technology (MIT). To make hydrogen cleanly and in bulk will almost certainly mean using renewable energy to electolyze water, though this process is costly and energy-intensive.

Current Energy Consumption of the World & Future Outlook

Today the world's primary energy consumption is about 11099 million tonnes oil equivalent (mtoe), whereof 88% comes from fossil fuels, 5.6% from nuclear and 6.4% from renewable energy sources (hydro, biomass, wind, geothermal). Crude oil accounts for 36% of global primary energy consumption and 40% of fossil fuels consumption.[6] There are indications that global conventional oil production has peaked and that we are heading towards an energy crisis in the very near future.

A good example to demonstrate the increasing need for energy in the near future and the eventual consequences if this is met by harnessing coal, is China. The ultimate potential of the Three Gorges Project, on the Yangtze, 18,000 MW, will still only supply a small fraction of China's needs over the next twenty years. It has been estimated that China will require an additional 600,000 MW over the next twenty years. This raises the question of what would happen to our planet if China approached the per capita electricity consumption of America and Europe and generated it from coal.[7]

With the expected decline in the global production of oil together with increasing demand, renewable energy sources like biomass, hydropower, wind, wave energy, tidal energy, geothermal energy and solar radiation are going to become increasingly important. In the long-term solar energy is likely to become the major energy source for humankind. Also ecological aspects such as the need to reduce greenhouse gas emission, as well as other polluting components like sulphur and nitrogen oxides are likely to promote increasing use of renewables.

As is the case of solar energy when harnessed, other renewable energy sources and nuclear energy in most cases will be converted into electricity. Whenever possible the electricity will be used directly, but there will always be a need for energy storage medium, like fuel to power land, sea and air transport. Obviously the number one candidate fuel is hydrogen. In principle any available energy source could be used to produce hydrogen.

The Case of Iceland

Iceland does not have to wait until harnessing of solar energy becomes economic. With its abundant hydro-energy and its geothermal energy, Iceland has already started the transformation into a hydrogen economy. This makes Iceland an attractive pilot country to participate in developing and improving the necessary hydrogen technology and to demonstrate the transformation into the hydrogen economy.

By the end of the 20th century Icelanders had already performed two major transitions in energy sources: to hydroelectric and geothermal. With the advent of the 21st century, Icelanders expect the third major transition. This century will also see a transition from conventional combustion engines to fuel cells. Hydrogen produced with electric energy from hydropower and geothermal heat is expected now to become the main fuel in the Icelandic transport and fishing sectors. In this way Iceland would be almost entirely free from imported fossil fuel and its greenhouse gas emission would be reduced below 50% of the present level.

The economically harnessable hydroelectric energy in Iceland has been estimated at 30 TWh/year and that of geothermal energy at 200 TWh/year of heat.[8] With present technology, 200 TWh/year of geothermal heat can be used to produce 20 TWh/year of electricity. Thus the total energy potential is 50 TWh/year. Of these 50 TWh/year only 8 TWh/year have been harnessed up to now (see Table 2).

Oil	Natural Gas	Coal	Nuclear Energy	Hydro electricity	Total
1.0	-	0.1	-	1.9	3.0

Table 2
Iceland's Primary Energy Consumption, 2006 (mtoe)
Source: BP Statistical Review of World Energy, June 2008.

If all imported fossil fuel were to be replaced by hydrogen produced from electric energy from domestic sources, an additional 5 TWh/year would be needed. Thus Iceland is in a rather unusual situation. Although only a small fraction of its domestic energy sources has been harnessed so far, one third of the energy used in the country comes from imported fossil fuel. This has inspired a study of the possibility of replacing imported fossil fuel by some synthetic fuel produced from domestic sources.

In the beginning, various alternatives were considered such as synthetic gasoline, methanol, ammonia and hydrogen, but over the past 15 years, especially after the breakthrough of the PEM fuel cell in 1993, the research work has concentrated on hydrogen. Because of the advantage that very high energy efficiency of the fuel can be achieved, it is believed that fuel cells will become increasingly important as engines in the 21st century.

Assuming for example a 100 MW plant and an electricity price of 0.02 US $/kWh, which is the estimated cost of electricity from power plants built in the near future, hydrogen produced in this way would be 2-3 times more expensive than presently imported gasoline when calculated on the basis of energy content.

In the case, however, where hydrogen is used to power PEM fuel cells currently in rapid development, the energy efficiency is 2-3 times higher than in conventional internal combustion engines. The reason for this is that in internal combustion engines the chemical energy of the fuel is converted into heat with a low efficiency because of thermodynamics limitations. In fuel cells, on the other hand, the chemical energy is converted into electric energy with a high efficiency. Fuel cells are free energy engines not Carnot engines.

Thus if both hydrogen production cost and energy efficiency are taken into account, the utilization of hydrogen produced from hydro-energy or geothermal energy in the Icelandic transport and fishing sectors could be almost competitive with present fuels.

Hydrogen Storage

The storage of hydrogen is a critical limiting factor promoting the use of hydrogen to power the transport and fishing sectors in Iceland. Hydrogen can be stored in numerous ways such as hydrogen gas, liquid hydrogen, hydrogen bound in metalhydrides and bound in liquid hydrides like methanol. Because of the large amount of energy needed to liquefy hydrogen, liquid hydrogen is about two times more expensive than hydrogen gas.

In a city bus fleet powered by PEM fuel cells hydrogen can be easily stored onboard as pressurized gas in sufficient quantity to operate the buses throughout the day (see Figure 3).The fuelling time is less than 7 minutes. A city bus fleet also can be operated from one fuelling station which makes no need for complicated infrastructure for the distribution of the fuel.

Storing hydrogen in private cars is not as simple as storing it in city buses. In prototype cars built until now, hydrogen has been stored onboard either as a pressurized gas, as liquid, in metalhydrides or bound in methanol. Private cars storing pressurized hydrogen onboard have only been able to run a short distance compared to gasoline powered cars. That, however, might change. Last year the Japanese company Honda presented a car, storing pressurized hydrogen on board, that can run 350 km on each filling. Three alternatives of storing hydrogen onboard are being considered: pressurized hydrogen, hydrogen bound in metalhydrides and hydrogen bound in methanol.

There are onging debates about whether fuel cells should be powered by hydrogen in a gaseous or liquefied state. The former is more energy efficient but also more difficult to handle. The latter is more amenable to mass consumption, but requires an impractically large storage tank. German automaker BMW is forging ahead with fuel tanks for liquid hydrogen, while most others have decided to use gaseous hydrogen.

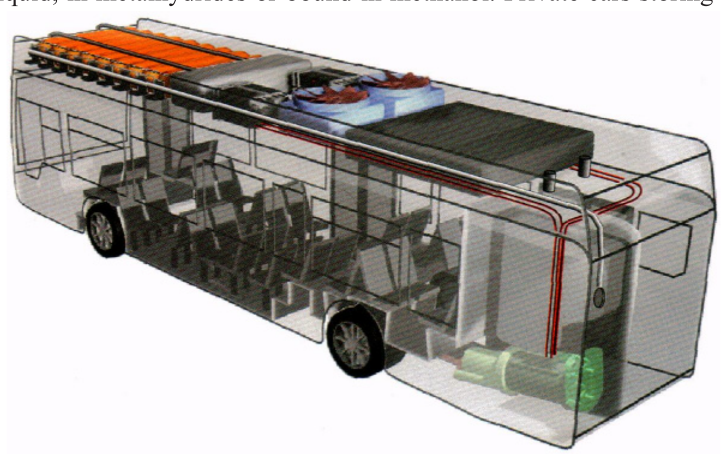

Figure 3
A Daimler-Chrysler Bus Powered by Hydrogen Fuel Cell in Reykjavick, Capital of Iceland

Source: Courtesy of Prof. Thorsteinn I. Sigfusson, Science Institute, University of Iceland.

As for powering the large Icelandic fishing vessels there are in principle no obstacles provided that fuel cells in the megawatt range become commercially available. These fishing vessels are at sea for up to six weeks and, therefore, need to store onboard large amounts of fuel. Consequently we can rule out the storage of pressurized hydrogen gas. Liquid hydrogen is a possibility, but as mentioned before, liquid hydrogen is very expensive and so is the technology needed to handle it. Therefore, the only possible near term solution for storing a sufficient amount of hydrogen onboard large fishing vessels seems to be to store it bound in methanol. Technically it is possible to produce sufficient methanol in Iceland to power the entire fishing fleet, by combining electrolytically-produced hydrogen and carbon dioxides currently emitted from the metals industry in Iceland. This could reduce the greenhouse gas emission from the fishing sector to about 45% of the current level.

Price may also be prohibitive in the early stages. The DaimlerChrysler buses introduced in Reykjavik carry a price tag of about $1.1 million each, equal to the price of four to five traditional diesel buses. Increased hydrogen production will inevitably lower these prices, but this economic barrier has prevented larger countries and regions from embarking on a full "hydrogenization" of their own. Iceland's government has done its share to offset costs: The parliament passed a bill exempting zero-emission vehicles from road taxes.

In 1997 a research team at the University of Iceland devised a roadmap to reach a hydrogen economy in Iceland. The following 5-phase scenario was suggested:

- PEM cell bus demonstration project. Up to three buses in public transport in Reykjavik.
- Gradual replacement of the Reykjavik city bus fleet and possibly other bus fleets by PEM fuel cell buses.
- Introduction of hydrogen-powered PEM fuel cell cars for private transport.
- PEM fuel cell vessel demonstration project. One research vessel with hydrogen stored onboard bound in methanol.
- Gradual replacement of the present fishing fleet by PEM fuel cell powered vessels.

The above scenario interested three big European companies, which in 1998 led to the establishment of Icelandic New Energy, a University of Iceland spin-off corporation created to promote hydrogen economy in Iceland. Icelandic New Energy anticipates 50 years of development towards the goal of replacing fossil fuels in the transport and fishing sectors. The company estimates that about 4.3 TWh/year of energy will be needed to complete the change using 81,000 tonnes/year of hydrogen .[9]

Iceland: Pioneering the Hydrogen Economy

Iceland had already undergone two energy revolutions in the 20th century. First the country's immense hydroelectric resources were tapped to produce electricity. Then, in the 1940s, geothermal water supplies were appropriated to provide the heating needs for all of the homes of Reykjavick as well as to produce a significant portion of the country's electricity (see Table 3). Hydrogen could spark the third energy revolution in Iceland's recent history.

Why hydrogen? In a word, unlike petroleum, hydrogen is a clean and unlimited fuel. And Iceland can use its already-developed and practically pollution-free hydro-electric and geothermal energy resources to produce it.

Most outside observers agree that Iceland is a uniquely well-qualified contender for this hydrogen experiment. The country has a relatively small population (290,000) – mostly concentrated in the southwest of the country around the capital – that is well educated (100-percent literacy). Also Iceland has higher per capita car ownership than any other country in the world.[10] Moreover, Icelanders are typically very environmentally conscious as the country's successful recycling programmes and clean air and water suggest. All these elements combine to help Iceland advance its reputation as the "Kuwait of the North".

	2005		2006	
	GWh	% of total	GWh	% of Total
Hydropower	7,014	80.8	7,289	73.4
Geothermal	1,658	19.1	2,631	26.5
Fuel	8	0.1	5	0.1
Total	8,680	100.0	9,925	100.0

Table 3
Electricity Generation in Iceland, 2005-2006
Source: Energy Statistics in Iceland, 2007.

Figure 4
The World's First Commercial Hydrogen Filling Station Reykjavic, Iceland
Source: Courtesy of Professor Thorsteinn I. Sigfusson, Science Institute, University of Iceland.

Iceland has designed an impressive plan to convert every personal vehicle in the country – of which there are currently over 180,000 – to hydrogen. The plan does not stop there, however. In the fall of 2003, the first three hydrogen buses began their scheduled routes on the streets of Reykjavic. They fill up at the world's first commercial hydrogen station, which opened on April 24, 2003 (see Figure 4).

By 2006, the first demonstration project for a fuel cell-powered ocean vessel was completed with current plans calling for a complete conversion to hydrogen of Iceland's 2,500-ship fishing fleet, beginning in 2015. These are ambitious goals and correspondingly difficult to meet, but the opportunity for future benefits has attracted major players in the energy industry to come to Iceland's aid. Among them carmaker, Daimler Chrysler, Royal Dutch Shell and Norway's leading hydroelectric company, Norsk Hydro. The European Union is also actively involved.

Moving to a hydrogen economy is not without problems. Iceland has been producing hydrogen for decades to use in fertilizers, so the technique is well known by the energy industry. Capacity rather than knowledge presents the most serious challenge: hydrogen production will have to be increased at least 30-fold to meet the expected demand a hydrogen economy would create. The preferred method, electrolysis, is a highly energy-intensive process, which makes hydrogen about three times more expensive by energy content compared to fossil fuel imports. But the PEM fuel cells that Iceland would use are up to three times as efficient as internal combustion engines, which will probably make hydrogen competitively priced.

Worldwide Interest

As Iceland moves forward with its hydrogen plans, other countries have taken a keen interest in the small island nation. Hydrogen stations have recently been opened in Tokyo, Hamburg and major cities in the Netherlands, Spain, Britain, Belgium and Sweden. Canada – like Iceland, abundant in hydroelectric energy – has also expressed a strong interest in the new energy process.

The United States is slowly acknowledging the benefits of hydrogen. The U.S. Department of Energy projects that by 2010 about 12 trillion kilowatt-hours will be replaced by hydrogen. By 2030, DOE aims to replace 10% of current U.S. energy consumption with hydrogen power.

Iceland is in a way serving as the model of the society of the future – the society which is environmentally sound; which is based on renewable energy and on a way of life which does not destroy the life or the atmosphere or the bio-system that we have. There is a lot at stake.

Conclusions

Iceland's gradual transformation into a hydrogen economy is a viable proposition given its abundant hydro-power and geothermal energy. Iceland, like Brazil vis-a-vis the ethanol production, could be a great success story since it fulfils the two essential conditions to make a hydrogen economy viable, namely vast hydroelectric and geothermal resources. Countries like Canada and Norway also meet the critieria for a successful hydrogen economy.

But such a transformation can't be replicated anywhere else yet without the massive use of fossil fuels, something that the hydrogen economy is trying to leave behind. However, with steady progress and a few significant technology breakthroughs, the world will start to make a committed switch to a hydrogen economy – over the next several decades a confluence of events will mark a steep increase in hydrogen energy development. By that time, hydrogen production costs will be lower, the basic components of a hydrogen storage and distribution network will be in place, and hydrogen-powered fuel cells, engines, and turbines will be mature technologies that are mass produced.

A hydrogen economy is destined to become a reality sometime during the twenty-first century and that hydrogen will become the "fuel of choice" and will be available for every end-use energy need in the economy, including transportation, power generation and portable power systems. At the time the vision for a hydrogen economy becomes a reality, several decades from now, hydrogen will still be produced not only from fossil fuels, but also from biomass and water using thermal, electric and photolytic processes. Hydrogen produced from water will be a cost competitive alternative to hydrogen made from hydrocarbons.

Footnotes

[1] Adam Piore, *Hydrogen Economy*, Newsweek April8/April 15, 2002, p. 62.

[2] Ibid., p.64.

3 Wikipedia, the Free Encyclopedia, p. 1.

[4] David Strahan, *Hydrogen's Long Road to Nowhere*, NewScientist, 29 November 2008, p. 41.

[5] Ibid., p. 42.

[6] BP Statistical Review of World Energy, June 2008, p. 41.

[7] Bragi Arnason, *The Road from a Fossil Fuel to a Sustainable Energy Economy: The Strategy in Iceland* (a paper to be Published soon), p.1.

[8] Ibid., pp.3-4.

[9] Ibid., pp. 4-5.

[10] Asgeir Sigfusson, *Iceland: Pioneering the Hydrogen Economy*, Foreign Service Journal, December 2003, pp. 62-65.