Implementing the hydrogen economy

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Abstract

In the Icelandic community the use of renewable energy and the tests with a clean domestic fuel that most people refer to as the fuel of the future have become the points of focus. In Reykjavik this future has arrived. Hydrogen is used currently as the energy carrier within the public transportation system and is electrolyzed from water with hydroelectric power and leaves the system as water again.

A small collaboration platform, Icelandic New Energy Ltd (INE), has been working on projects related to hydrogen as an energy carrier since 1999. A number of projects and feasibility studies are currently being carried out in Reykjavik, revolving around the issue of making hydrogen domestically from water and renewable energy (hydro and geothermal power), abundant local resources.

In April 2003 the first electrolytic hydrogen production, compression and filling station was inaugurated in Reykjavik. The refueling station is designed to be open to public services. The hydrogen station is a delivery to be tested within the project ECTOS, the Ecological City Transport System—a fuel cell bus demonstration running between 2003 and 2005. A socioeconomic and environmental research methodology has been established and followed for three years now. The outcomes of ECTOS are needed to establish the basis of further decisions of integrating hydrogen into societal functions. Amongst the undertakings is a forecast for the scale and costs of the essential infrastructure. General surveys have shown that Icelanders have a high general acceptance towards using hydrogen as a fuel for the transportation sector and fishing vessels. Therefore it is presumed that hydrogen fuel stations need only to be established in a limited number before hydrogen fuel vehicles can be introduced in the public market. Yet, a realistic time-frame depends on the hands-on experience, the performance and availability of the equipment in the market. In 2005 the outcomes and experiences from the ECTOS project will be published.

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1. Introduction

Given the rising concern for carbon dioxide and other types of emissions and the ever growing demand for energy and fuel, many governments are redrawing their roadmaps with regard to transportation and energy systems. Hydrogen is currently on the list of buzz words included in governmental policies. But in Iceland, the hydrogen option is not only a future vision but is already being tested and implemented as an energy carrier. While testing the performance of the technical feasibility to safely operate fuel cell buses within the public transport system, the opportunity was taken to also scrutinize many of the environmental and socioeconomic aspects of the usage of hydrogen as a fuel. The test may facilitate an early introduction of hydrogen and vehicles using hydrogen in the Icelandic market. In this document, readers are provided a general insight into what is considered of interest in this context; a few of the preliminary results are described.
2. Optimal conditions

There are several reasons why the republic of Iceland is ideal to take the course for hydrogen as a fuel within the transportation system, even while the hydrogen technologies are in early stages. Firstly, Iceland has bountiful sources of fresh water and renewable energy. This new type of fuel will be generated with the splitting of water into oxygen and hydrogen in an electrolytic process. The national economy relies, to a large extent, on the income from fisheries and therefore, depends highly on using oil in fishing vessels, agricultural vehicles, cars and buses.

The need for energy in all other sectors is already fulfilled by renewable sources: industry and households enjoy electricity generated either by hydro- or geothermal power and heating is by geothermal sources (Fig. 1). In 2001, 18% of the electricity on the national grid was generated by geothermal steam turbines and this portion will be increased within the next decades [9]. Electricity for all other needs is generated from hydropower and therefore approximately 70% of the total energy demand of Iceland is produced from renewable energy sources. The other 30% comes from oil, which is used exclusively for transportation, agricultural vehicles and the fishing fleet. Around 90% of industrial plants, households and services are connected to district heating systems or to local hot springs that provide them with steam for process heating or hot water for drying, heating, washing and cooking [8].

Secondly, there is a definite political commitment towards further extension of the use of renewable energy. In 1998 the Prime Minister, the Minister of Industry and the Minister for the Environment signed a statement wherein they proclaimed:

“Further development of the domestic energy resources is on the Icelandic Government’s agenda. The aim is to harness these in order to diversify the economy and lay the foundations for higher living standards and prosperity in the future. One of the possibilities under consideration is the production of alternative fuels such as hydrogen that could replace oil in the transportation sector, i.e. for cars, airplanes and fishing and transport vessels. In addition to diversifying the economy, such use would contribute significantly to reducing the emissions of greenhouse gases.”

The third reason is the growing fear of the insecurity of fuel deliverance to this island nation that cannot easily connect to energy services in the neighboring countries. The recent dramatic increases in the prices of oil products still urge to plan for fuel independence. In addition there are no local carbon sources available in the country, even the vegetation and soil have poor cover and biomass is scarce because of the short growing season and the history of severe erosion. All fossil fuels are therefore imported. This remarkable situation makes hydrogen probably the best local choice for fuel, while other countries may well settle for carbonated renewable fuels as their sustainable alternative, for example

Fig. 1. Iceland covers about 70% of its energy needs with renewable energy. Yet some air pollution from transport and traffic is visible on still winter mornings. © Icelandic New Energy.
ethanol made from organic residues. Gas is a common energy carrier in the European continent and predictably gas is to become the main source of energy for the next decades or even centuries. During the 20th century, natural gas was only used for a short period of time in Reykjavik, mostly in street lighting, but it was soon replaced by electricity, generated by the first hydropower plants. Only recently has the waste management company of Reykjavik (Sorpa) begun tapping off methane from its landfills and can offer their product as fuel for a few hundred cars.

A fourth reason is that the energy needed to produce hydrogen for all land and marine transport in Iceland is estimated to be around 10% of the available, unexploited national renewable energy sources [19]. In 1994 [5] the Icelandic energy authority estimated that in total it would be feasible to generate the amount of 50 TWh annually from hydro- and geothermal sources [12]. At the same time the total energy needs for the transportation and fishing sectors in 2030 is estimated to be about 100,000 metric tons of hydrogen. Using accepted conversion efficiencies for electrolysis and fuel cells, this amount of hydrogen translates into an electricity consumption of approximately 5 TWh, or about 10% of the total available renewable energy that could be utilized.

A final reason for the suitability of Iceland to integrate hydrogen into its current energy settings is the fact that Icelandic know-how, especially within the geothermal field, is held high in esteem internationally. The technologies of hydrogen generation and use can easily be integrated with geothermal applications and stand-alone energy systems. One concept of hydrogen generation under study is electrolysis driven by an energy mix of heat and electricity [20]. Early results indicate that the amount of electricity use can be reduced drastically by applying heat to the electrolytic process thus saving the best energy quality and using instead an energy source which is in lower demand. If an environmentally sound and cost-effective way of producing hydrogen from water is developed, then all local requirements for energy can be fulfilled entirely by renewable energy in Iceland.

Despite the unique and optimal conditions in Iceland, the idea of an early transition to a hydrogen economy is also generating international enthusiasm. The European Union has sponsored some of the hydrogen projects in Iceland and expects to be able to transfer the results throughout the European Community.

3. The organization, Icelandic New Energy

The initial concept of shifting from imported fuel to hydrogen was developed at the University of Iceland and was brought into the academic discourse as early as in the 1970s. Mr. Bragi Arnason, Professor of Chemistry, began to introduce his ideas of locally made hydrogen as an energy carrier to his students and then to the public. The oil crises struck in Iceland as hard as elsewhere, subsequently, the idea of making fuel from water by electrolysis has moved slowly yet securely forwards.

In line with the governmental energy policy the key Icelandic power companies founded a cooperation platform in 1998 along with the University of Iceland and IceTec (the semi-public technological research institute). The Icelandic New Business Venture Fund supported the initiative financially and in 1999 Icelandic New Energy (INE) was founded as a microcompany. Three international concerns (Norsk Hydro, Shell Hydrogen and DaimlerChrysler) joined the venture, whose mission became to “investigate the potential for eventually replacing the use of fossil fuels in Iceland with hydrogen and create the world’s first hydrogen economy” [4]. This type of cross-sectional and cross-cultural organization has been very successful. The knowledge accumulated within INE but undertaken projects sprout from merging the ideas of many experts in other fields of energy and technology. Yet, manufacturing is not a part of INE’s undertakings, only the dissemination of ideas, management of joint projects, facilitation and integration and problem-solving at the implementation stage. The main task so far, has been to test the use of gaseous hydrogen and fuel cells as the driving technology within public transport.

4. Key projects

There are 3 strategic steps in INE’s plan to realize its mission. As shown in Fig. 2 the first is to test hydrogen fuel cell buses within the public transport system. For this purpose the project, “Ecological City Transport System” (ECTOS) was launched in March 2001. It is sponsored by the Commission of the European Union and 11 partners collaborate and put in their share of the budget and the work. The second step is to facilitate the introduction of personal hydrogen vehicles. At this stage a hydrogen fuel station is in operation, therefore the introduction depends more on the readiness of the car manufacturers to offer their goods at such a small market. The third one, but not the least important, is to test hydrogen and fuel cells in maritime conditions, especially, on fishing vessels.

Fuel cells are vulnerable to conditions that interfere with conductivity and electrochemistry. Therefore,
seawater and salty winds may prove to be problematic in a field where security is essential. A few preliminary studies have been made to prepare for the stepwise introduction of hydrogen on board fishing vessels. At first, only the auxiliary equipment on board will be run by fuel cells and later the move will be made towards a more ambitious project and use in the main propulsion engines, hopefully around 2010 [13]. It has still not been finally decided which type of hydrogenated fuel will be chosen for the vessel but several options are being studied.

The ECTOS, a fuel cell bus project is by far the largest undertaking of the company until now. The main focus of this paper is a discussion of the aspects of the transition towards hydrogen using the early experiences from ECTOS.

5. ECTOS and applied measures

The preliminary driving tests of the fuel cell buses were scheduled to last for two years but ECTOS is a four year international pilot project. The organization and preparation took two years. Three buses have now been operated since October 2003 on normal routes within the Reykjavik public transportation system, and the hydrogen fueling station has been operational since April 2003. The bus drivers fill the vehicles daily; their route is approximately 180 km during one shift. Then the buses are cleaned and inspected for overall performance.

The first task within the study was to develop an integrated methodology, pinpoint the critical aspects and find approaches to measure or account for them. Thereafter the tasks were allocated to the main actors in Iceland, Norway, Germany, the Netherlands and Sweden. The main goal of the data collection was both to learn and to spread general information. (However since some of the results are business sensitive, they are restricted, at this time, for internal use only [10].) However, the data collected have been the source of student projects within several universities and institutes and are thus spread to raise interest and give multiple parties the opportunity to learn from the implementation experiences.

The main goal of the ECTOS was to obtain as much practical experience as possible from the performance of the demonstration during the test period. Parallel to the technical performance test, a study on socioeconomic and environmental aspects was undertaken (Fig. 3). A few of the first indicators are reported in this document. The final results will be obtained and made public in April 2005. ECTOS has acted, in many ways, as the forerunner of CUTE, the larger project on Clean Urban Transport for Europe, and a similar test in 10 European cities and in Perth, Australia, and Beijing, China, with fuel cell buses under various conditions [2].

6. The refueling system

A major milestone towards the introduction of hydrogen was the completion of the first hydrogen electrolytic station designed to produce, compress and dispense hydrogen fuel in situ. The station, which is pictured in Fig. 4 was planned, designed, tested, erected and inaugurated in April 2003. It has been safely operated for over a year.

Plans for implementing a hydrogen economy quickly raises questions about costs, safety, as well as urban and community planning, timeframes, estimation of the total investment, regulations and taxation and the role of the
administrational bodies to bring the plans forward. Therefore, in a second INE project (2001–2003, the EURO-HYPORT [6]) a study was undertaken to clarify the detailed requirements of the first station: land use, production capacity, material requirements, distribution patterns, the required safety measures and expected efficiency.

On the basis of these studies and plans an extrapolation was made to predict alternative scenarios for hydrogen production on a larger scale, its distribution and optimal storage. EURO-HYPORT was meant as to give a preview into the future prospects without too much detail and as a preventive measure for the first undertakings of the “hydrogenization” to lead to a dead end. A section of EURO-HYPORT is focused upon issues pertaining to future type and size of an infrastructure as well as distribution patterns that might be required within a given future scenario and according to energy forecasting for Iceland as a holistic hydrogen-based society. Included are land vehicles where Iceland is pictured as a holistic hydrogen society. The study includes the fuel demand from fishing vessels, agricultural machines buses, vans and personal cars, in short all vehicles except those that could load their fuel in international ports. Hydrogen would only be used within the transport sector and for the propulsion of small, medium and large trawlers and ferries in that scenario. International flights and marine freight and household electricity as well as heating are not included for reasons explained earlier. The reader is hereby informed that military requirements in Iceland are nil.

Data on the forecasted number and types of vehicles, fuel cell efficiency, and quantities of oil used within the current fuel distribution and seasonal variations concerning the usage of fossil fuel were obtained from public sources and analyzed. This led to an evaluation of the required production capacity for hydrogen at different locations and for different user groups like land transport in each region as well as for the fishing vessels (Fig. 5).

While finding the optimum unit sizes for the Electrolyser, storage capacity and distribution methods, the indications are that electricity prices play a major role in determining production costs. Long distance transportation of hydrogen is expensive and therefore the hydrogen should preferably be formed locally and the electrolysis fueled by local power stations, or the electricity might be distributed from larger power stations towards the main hydrogen markets. It is foreseeable that the transition will take a long time and the needed distribution system therefore added stepwise according to local demand for hydrogen.

The estimated acceptance for hydrogen usage in Iceland is very high (see discussion in a later section). This should be directly correlated with how easily and fast the new fuel technology will be accepted in society given that prices would be similar. A crucial question is: How many fuel stations will be needed so that consumers become willing to shift to a hydrogen-powered vehicle, given of course that the price is acceptable. Consumers, in this context mean the normal public, not just fleet operators. Because of the generally
positive attitude of the public, there are indications that even low availability of hydrogen might fulfill the acceptance criteria of the user. The inhabitants of the Greater Reykjavik Area amount to 2/3rds of the total Icelandic population. There are three main traffic axes towards the city center. Strategically chosen locations for hydrogen stations around these key roads might be sufficient to fulfill the first customers’ acceptance criteria. With these sited on the key roads and 3 more hydrogen refueling points, all consumers in the area will be within a 6–10 km radius from a hydrogen station during their daily routes; most consumers would pass one of them during their daily commute.

Iceland is very mountainous and 99% of the inhabitants live close to the seashore (Fig. 6). A single circular highway passes through most villages and service centers of the rural communities. In many small towns there is only one fuel station serving the settlements and the traffic on the main highway. The oil, which is delivered in the area, is also utilized by the operators of fishing vessels. The circular highway around Iceland is only 1400 km and with hydrogen filling stations in villages at an interval around 150–200 km, then 10–15 hydrogen filling stations would serve customers living in the rural areas and give customers the freedom to travel at their leisure at least on the main roads. The results of EURO-HYPHORT study indicate that the infrastructure needed to create public acceptance for hydrogen in all of Iceland would cost 3.5 billion Euros and the total transition costs would be about 5 billion Euros (approx 7 billion US$).

Currently there are 55 filling stations in Reykjavik and 175 stations in the entire country. The latest trend is to decrease their number and to make them automatic. Therefore, in order to tempt customers to turn to hydrogen vehicles, it may only be necessary to convert 10–15% of the total number of filling stations to hydrogen and in that sense, facilitate the introduction of hydrogen vehicles. Where land space is scarce, an
electrolysis station could even be placed within or on top of other types of fuel stations.

7. The first hydrogen station

Actually building the first fuel station within the ECTOS became a practical training lesson.

It took awhile to find an optimal location for the hydrogen station, but the local oil company Skeljungur and Shell Hydrogen collaborated efficiently in finding a site and in constructing the facility. Inside the station walls no trespassing is allowed, but the walls are transparent and visitors can easily see the components and read about the process on the information panels both in Icelandic and English. The station was delivered from Norsk Hydro electrolyzers and includes an electrolytic unit, a diaphragm compressor and a dispenser [14]. The electrolysis occurs under light at a pressure of 11 bars. The station’s storage cylinders keep hydrogen gas under a 440-bar pressure. The storage tanks on board the buses are filled with approximately 50 kg of hydrogen each day. All material, connections, valves etc. must be made of materials that are resistant to hydrogen embrittlement and hydrogen corrosion.

Neighbors to the station did not file complaints or make any negative comments about the plans to construct the hydrogen station in their vicinity, neither did they show concern by asking for further information but asked for an invitation to the inauguration! This can be interpreted as trust in those who were responsible for the planning and construction of the station and it reflects the very positive attitude on behalf of the public, at large, within Iceland.

Outside the station walls, a distance of 13 m is maintained as a zone free of obstacles. But a normal petroleum filling station is its next door neighbor. The hydrogen facility has no roof, so that possible leakage of hydrogen may diffuse into the air. The station is also equipped with hydrogen detectors that will give a sound alarm and stop the production in case of a hydrogen leak.

The hydrogen station is attractively designed. Visitors in Reykjavik often stop to take a closer look on their way out of town; it stands on the right side of the main road that connects Reykjavik to ‘Highway No 1’. The operations are monitored through a computer system and the process can be remotely controlled. The process of the station and the role of the various components are explained in INE’s Second News Letter on the company’s homepage (http://www.newenergy.is).

It became evident that governmental officials had no previous experience in issuing licenses for this type of service; therefore it took some time for the administration to address subjects related to new uses of hydrogen and to issue permits that are compatible to international safety and usage requirements. The local safety authorities agreed to follow frameworks and safety standards, which were established in Germany and Norway [1,3]. It was, however, essential for this information to be available in Iceland before further development could occur.

8. Salty winds and vulnerable electronics

The fuel cell buses were pre-tested in Mannheim, Germany and the technology was adapted for usage under their conditions. The acceleration of the buses was found to be quite satisfactory.\(^3\) Safety measures were very strict within all hydrogen equipment in order to prevent any mishaps. A computer system monitors what is happening within the fuel cells and the adjacent equipment on board the buses. The safety equipment is designed to stop the vehicle if there is any indication of leakage or malfunctioning of the drive train or the fuel supply during operation. The electrical motor that powers the bus is fed by the current from two 115 kW fuel cells; to ensure this operates properly, the electronics and conductance are of specific importance in this type of drive train. Therefore, one of the main concerns was the effect of the humid weather and the windy conditions in Reykjavik, which carry salt particles from the sea that often interfere with electricity transmission on the national grid, even far inland. Another factor is the rapid variations in temperature and the effects of wind cooling on fuel consumption.

The results revealed that during the first months of bus usage, no failures due to salt effects were reported. The electronics did not show more frequent failures in Reykjavik than for identical buses that were tested during the same time in Stuttgart, Germany in context with the larger CUTE project. The fuel consumption was found to be considerably higher during cold spells in February.

The bus carries most of the hydrogen equipment on the specifically strengthened roof (Fig. 7). In case of any leaks, the hydrogen will rise and diffuse quickly into the atmosphere. The storage bottles on top of the buses keep the hydrogen gas at 350 bar pressure; refueling takes about 10 min. The temperature rises during the filling of the storage containers but the dispenser is equipped with a pressure sensor that monitors the filling and keeps the fuel flow within proper pressure ranges. The daily fill of hydrogen (around 50 kg) allows the buses to be driven 150–200 km, which is a normal one-shift route of a public city bus in Reykjavik. Some of the heat that develops from the drive train is channeled to heat the interior of the bus. If needed, additional heat

\(^3\) According to 11 out of the 15 trained drivers the acceleration is the same or better than of the diesel buses they are used to driving. Survey conducted amongst the drivers in ECTOS, January 2004. Four did not send in the questionnaire.
can be generated from a secondary, hydrogen-driven heating system. But the specific cooling system that is a standard feature of the Citaro fuel cell buses from EVO BUS was not often needed in Reykjavik. This part will probably not be included in the future design of FC buses to be driven in similar latitudes, even though cooling may be essential in regions such as the Mediterranean area [2].

It is generally known that cold starts for fuel cells can be difficult and temperatures below freezing point can damage them. This was taken into account in Reykjavik during the first driving season itself. The maintenance shop is run in facilities that belong to the dairy in Reykjavik. The dairy trucks, which run on diesel fuel, are always connected to motor heaters while they are idle. This is a normal procedure in many companies in cold climates. This keeps the motors lukewarm and boosts the fuel efficiency of the vehicle. The fuel cell buses were simply connected to the same equipment; a motor heater was connected to an electricity cord. This way the fuel cell on board the test buses (and the internal combustion engine of each milk truck) always stays above freezing. Problems with cold starts have not been reported. However the climate is not as cold in Reykjavik as people may anticipate; the average winter temperature is about 0°C.

The performance of the bus was better than expected for a prototype. Plans had accounted for the possibility that out of the three buses it would be justifiable if only two would be available for usage each day. However, the fuel cell buses have proven to be far more reliable. The only reasons for stoppages were due to logistics concerning drivers’ shifts and bus routes and their holidays, a problem that was easy to overcome. Only 15 drivers were trained to serve as conductors for the fuel cell buses. Instead of running the buses always on the same route the buses were simply brought to the appropriate drivers wherever they were serving their shift inside the city bus system [17].

9. Total costs and real prices

The Reykjavik hydrogen Shell station was tailor-made to fit its applications within ECTOS and became a good representative for the emerging hydrogen technology. The station cost approximately 1,000,000 Euros including the specific design and in situ technical solutions.

The price of the hydrogen from the station is driven, to a large extent, by the price of the electricity used for the electrolysis. As long as hydrogen is made in small stations the electricity costs are the same as for any other small user [7]. On the other hand it is expensive to store and transport hydrogen, both as a gas and as a liquid. The price of land for storage is rather low in Reykjavik but can also become an influential factor in the fuel price because of the bulky nature of hydrogen or due to imposed security zones.

Fig. 8 and a list of scenarios considering various proportional penetration of hydrogen in the market show the expected decrease of air pollutants. It is generally accepted that fuel cell vehicles will most probably serve at the beginning as an option within public transport. The fuel cells and hydrogen containers are bulky and need much space unless the pressure is raised considerably. Also, buses that use diesel oil as a fuel give rise to unhealthy air emissions in urban areas and also to the particles that damage cultural monuments, buildings and other equipment. Using fuel cells and hydrogen in city centers is a good option to seek to reduce both problems. But, eventually personal vehicles, which give rise to a large part of the local air emissions, must also be brought into widespread usage.

The presented forecast of changes is based on measurements within ECTOS and the composition of exhaust from buses in Reykjavik. At the outset (Scenario 1) it is stated that all buses and 50% of trucks are already driven on hydrogen but what changes are to be expected if the ‘hydrogenisation’ goes even further? Normally most air pollution (CO₂, CO, hydrocarbon residues (HC), nitrogen oxides, NOₓ, sulfur oxides, SO₂ and particulate matter, PM) arises from traffic and the proportions are correlated to the types of cars, their sizes, types of fuel, their combustion technology as well as the fuel efficiency and the proportions of cars in each category. Icelanders mostly drive their own vehicles and even large models, hence the large changes in emissions of carbon dioxide, nitrogen oxides and carbon monoxide. But in Reykjavik it is evident that the level of sulfates from geothermal sources in the city and the level of particulate matter that is mostly derived from studded tires and wind blown soil particles will not change much even though the bulk of the traffic runs on hydrogen, which is very close to being emission free except for water.
The costs for hydrogen will be calculated based upon all the parameters that were tested during the ECTOS demonstration, but this cost will not be a good representative of the cost of hydrogen in the future because the ECTOS project is not designed to test maximum efficiency or the optimal running of either the fuel station or the buses, but simply to see if the performance of the equipment makes such a system possible and feasible for further development. The next generation of fuel cells, bus design with its auxiliary components, etc. will be different from the system that is currently being tested. Therefore, it was decided to set the price of hydrogen in the following manner: The costs of driving on hydrogen should not become more than 20% higher for a given distance than the same ride on taxed gasoline. Or if the fuel cost is 100 kr to drive diesel bus X km then the cost of driving the same distance on hydrogen should be 120 kr. This price was set as the goal for the costs within the next 20 years.

This indicates that the investment cost that went into the ECTOS hydrogen station will not be paid back during the project period. Also, the comparison is between untaxed hydrogen and taxed gasoline.

For the present time, a rough estimation of the actual costs of running the Reykjavik hydrogen prototype system is about 5 times more expensive in operation than running a similar system on gasoline at the price of gasoline as of June 2004. The actual costs and simulations from Reykjavik will be kept as internal information for the project for later benchmarking purposes. Yet it should be considered that external costs are, of course, incorporated in the hydrogen system while fossil fuels are still not charged for those same external costs. It is also inappropriate to compare the costs of running a petroleum infrastructure, which has had 100 years to adjust to its current price levels [16], with the costs of using one prototype hydrogen station that offers services for only three vehicles. For further comparison of total costs using various drive trains, so called life cycle costs, the reader is referred to Joan Ogden’s discussions on this issue [15].

A schematic representation of the societal life cycle costs from Ogden et al. is presented in Fig. 9. It shows the price of air pollution, costs of fuel supply security and in addition the foreseen costs of emerging driving technologies to compare these with the costs of the systems to which we have grown accustomed. According to the published results of their research team, the societal lifecycle costs of fuel cell vehicles, which run on hydrogen made with wind power, are lower than those of the current gasoline SI internal combustion engine vehicles. Using hydropower and geothermal power to produce the hydrogen would reduce the costs even further.

Within the ECTOS project, a life cycle assessment (LCA) of the impacts of using the new hydrogen technologies in Iceland has been conducted [11]. The largest impacts will be the ones inflicted during the use phase of the vehicles, but because of the unusually low emissions to the atmosphere from the hydro and geothermally powered electricity generation in Iceland compared for example to the grid mix in Germany, the Life Cycle Impact is very low except for one factor — the emissions of sulfur-compounds from geothermal vents in high heat geothermal areas [18].

A specific technological method already exists to trap these emissions at the source. In the end the emissions from transport and the fishing fleet should be slashed by almost 90% if hydrogen becomes the energy carrier for these sectors. The expected changes in air pollution in Reykjavik are also large according to the ECTOS midterm environmental report [18]. Fig. 8 shows the main results when eventual changes in air quality are plotted against selected scenarios in hydrogen use. If all

<table>
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<tr>
<th>Scenario</th>
<th>Buses all hydrogen driven</th>
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<tr>
<td>Scenario 1</td>
<td>100% buses, 50% light trucks, 15% petroleum passenger cars hydrogen powered</td>
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<tr>
<td>Scenario 2</td>
<td>100% buses, 50% light trucks, 30% petroleum passenger cars hydrogen powered</td>
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<td>Scenario 3</td>
<td>100% buses, 50% light trucks, 50% petroleum passenger cars hydrogen powered</td>
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<tr>
<td>Scenario 4</td>
<td>100% buses, 50% light trucks, 70% petroleum passenger cars hydrogen powered</td>
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Fig. 8. The expected changes in air quality in Reykjavik compared to various scenarios for hydrogen penetration on the market. © Icelandic New Energy.
buses, 50% of light trucks and 50% of personal vehicles were to be run on hydrogen then up to 50% drop in carbon dioxide, carbon monoxide and airborne hydrocarbons can be expected. Yet, particulate matter such as dust and tar particles would not decrease as much because they are not so much derived from the burning fuel as the asphalted roads that are torn up by studded winter tires.

10. Early indications of public acceptance

Various approaches were used to collect data within the socioeconomic and environmental research in ECTOS. They were carefully designed to engage many levels in society and various disciplines. In a way, the approach to the data collection was at the same time a way to spread information about the project and eventually to raise interest in the field. Fig. 10 shows, for example, a scene from the first fuel efficiency tests. The association of elderly people was offered to participate in the study and create the needed weight for fully loaded and half loaded buses. A hundred and fifty volunteers were willing to help out, but only about 80 were needed.

The first public survey was made to serve as a standard reference for later tests on the social acceptance. An initial public survey was made in December 2001. The Institute for Applied Sociology of the University of Iceland performed a telephone survey and asked 1154 people about issues related with hydrogen. The first question was whether people had heard about Icelandic New Energy and only 22% claimed to have heard about the company. Somewhat fewer people claimed to know what the company is dealing with (20%). Then the respondents were asked the following question: Do you have a positive or a negative attitude towards the option of using hydrogen as the main fuel for buses, ships and cars. The respondents could then indicate a very positive, positive, neutral, negative or very negative stand towards this
option. The results indicate that 93% of the respondents took a positive or very positive stand and only 3% stated they were against the idea. Finally the last question posed was: Do you feel that there is a need for more information about the hydrogen technology. Twenty-two percent of the respondents admitted that they would like to learn more about hydrogen technology, especially the young people and women. Gender or age did not play a role in the attitude towards using hydrogen as a fuel.

This outcome was more positive than expected whereas the public was said to take a rather negative stand towards innovations that do not have a known beneficial function. A plausible explanation might be that, hydrogen as a fuel, has been in academic and public discourse on and off since the 1970s.

Within the ECTOS a second survey was conducted on board the buses in March 2004 and the passengers and other commuters in Reykjavik were engaged in more detailed questionnaires on hydrogen and energy issues. An important feature was to check on the individuals’ willingness to pay for fuels that are clean and made domestically. The results of these questionnaires are to be translated and turned in as a deliverable from the ECTOS project.

The survey made amongst the passengers of the hydrogen buses and more conventional buses gave very similar results concerning attitude towards using hydrogen as the main fuel (86% replied positive and very positive to the same question as posed in December 2001).

Passengers, neighbors to bus routes and people in the street were asked about their first connections to the concept ‘hydrogen’. A vast majority of the respondents connected hydrogen to water, clean fuel and clean environment, even though they were given the option of ticking for explosions, burning Zeppelins and expensive technology. When asked for their willingness to pay a higher fee for hydrogen during its introduction, people showed understanding and a majority said that they would be willing to pay 10–20% higher prices for hydrogen during the introduction phase. To support this stand, a respondent was quoted: “After all bio-products or ecologically friendly services usually need to cost a little more”. Those who were against paying higher prices would support their view with comments like: “Well hydrogen is made from water. We have plenty of water in Iceland and therefore, it is just evident that it should be cheaper than oil”.

The questionnaires were designed to give a profile of the aspects that are relevant in this context and will be used mostly to benchmark specific aspects during the first stages of the introduction of hydrogen. There are various issues, such as: Does the public fear hydrogen? Are there barriers to the public’s acceptance of the infrastructure that depends on public goodwill? Do people recognize there is less noise or a different pitch to be expected from fuel cell vehicles? Do the neighbors appreciate less noise from bus traffic? All of the results will be published by April 2005 at the final conference for the ECTOS.
Results of surveys, preferences, technical performance, costs, etc. will then be used to draw the general profile of hydrogen as a fuel in the societal context. To name a few aspects that may also be relevant to map further on are: job creation and needed education, net balance of import and export of energy, awareness and value of environmental issues, air quality and health costs as well as real measurements on the total fuel chain efficiency. The ECTOS is a fine base for further studies. All these pieces of information are helpful to decision-makers who need to plan for a sustainable energy system that suits common goals and social development.

The reports will be presented to key persons within governmental bodies so that the people who can influence decision-making will have a basic understanding of the opportunities implied. It remains to be seen if there exists the political will to facilitate the implementation of a hydrogen economy and to select the appropriate steps for such development, but bringing real test results into the discourse may fundamentally speed the pace of change.

The approach described above for the integration of hydrogen into the local settings is rather typical of the way Icelanders work: First they take actions and learn (and probably waste money during the episode) and then the learning is used for further planning. This was the case for the first Icelandic geothermal power plants in the 1970s for example, but the rewards are probably still filing into the local economy. Although, this may seem like irrational behavior, there is a rather good consensus on this approach among the key players. The gains from learning by doing must seem to be higher than the monetary spending; no doubt this shows both the political will to facilitate the implementation of a hydrogen economy and to select the appropriate steps for such development, but bringing real test results into the discourse may fundamentally speed the pace of change.

11. Conclusions

Being independent of fossil fuel imports is quite a challenge for a small economy like Iceland. But given the optimal conditions, the goodwill of the public, the political support and the consistency to make use of local renewable energy, a hydrogen economy may be realized in Iceland within the next few decades. Even though the initiative has its roots in many unique Icelandic features, the media attention given to geothermal and the hydrogen initiative indicates that the rest of the world is intrigued. Expectations towards using the results as a foundation for future policies are high; representatives from international institutes, industries, news agents, students, and foreign politicians are daily guests in the Icelandic energy companies. Professor Bragi Arnason, a true visionary of the local hydrogen economy, has stated that it has usually taken 50 years in the Icelandic past to shift entirely from one energy infrastructure to another, but other countries report a quicker transition to methane-gas once the decision had been made.

The hydrogen economy is foreseen as an important piece of a sustainable transportation system in the Icelandic context. Its limits are not set by the evolution of the appropriate technology; the speed of the development is rather based upon the allocation of resources and the will to take on the challenge of moving towards a cleaner future.

References

[3] Det Norske Veritas (http://www.dnv.no) has been cooperating with Norsk Hydro to establish both internal and national hydrogen safety standards for Norway. A recommended report on the issue is Ref. [1].
[13] New-H-Ship is currently in first stages of preparation; further information by skulason@newenergy.is.


