ECOLOGICAL CITY TRANSPORT SYSTEM

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1. PROJECT GOALS

In 1997, a committee appointed by the Icelandic Ministry of Energy to investigate the possibility of domestic fuel production, recommended that efforts should be directed towards hydrogen and hydrogen-rich artificial fuels, eyeing the resulting savings on imported oil and greater energy independence. As a consequence, in 1998, Icelandic New Energy Ltd. was formed with 51% of the shares owned by a consortium made of the Icelandic New Business Venture Fund, Icelandic corporations in the energy sector, and two major institutions. The three international corporations, DaimlerChrysler, Norsk Hydro and Shell Hydrogen, joined as founding members rounding up the remaining 49% of the share capital.

The aim of the company was to set up a joint venture to investigate the potential of eventually replacing fossil fuel usage in Iceland with hydrogen-based fuels and ultimately to create the world's first "hydrogen economy". University of Iceland Professors Thorsteinn I. Sigfusson and Bragi Arnason together devised a roadmap to achieve the hydrogen economy, outlining the guiding goal of the nascent Icelandic New Energy. The strategy was to begin with the introduction of a hydrogen-powered fuel cell bus test-fleet. The next phase was to promote the integration of fuel cell powered vehicles for passenger use. The final phase consisted of examining the possibility of replacing the fishing fleet with hydrogen-based vessels. These simple guidelines still stand.

Icelandic New Energy, under the general management of Jon Björn Skulason began preparation for a demonstration project, which sought financial support from the Fifth Framework Programme of the European Union (EU). The project was called ECTOS (**E**cological **C**ity **T**ranspOrt **S**ystem). Its main objectives were:

- to construct a hydrogen fuelling station completely integrated into an urban setting, and
- to feed three hydrogen fuel cell buses in the regular public transport fleet of Reykjavik for a test period of two years.

The basic ideology behind seeking support from the EU was the following:

- Iceland has unique circumstances to make it possible to operate a hydrogen-based fuel project in a CO_2 neutral environment.
- Iceland standards and transportation systems are similar to those of most other developed countries. Therefore it is important that the project makes a big impact, i.e. that it be a real-scale project. Three buses out of a total 100 buses in Reykjavik represent a sizeable portion.
- The new technology needs to be evaluated under severe weather conditions.
- The government of Iceland has announced that it is aiming to transform Iceland into a hydrogen society in the near future.
- The results can easily be adapted elsewhere.
- Iceland has recent experience in converting from one energy source to another, i.e. from fossil furnished heating systems to a geothermal district heating.

After an evaluation by a panel of experts, the EU decided to support ECTOS with 2.85 million EUR (3.4 million USD, at an exchange rate of .846 EUR/USD) out of the total cost of 7 million EUR (8.3 million USD).

2. GENERAL DESCRIPTION OF PROJECT

The ECTOS project was launched on March 1st, 2001. It was divided into a two-year first phase which involved preparation, establishing infrastructure including a maintenance facility, and designing methodology for socioeconomic impacts research, etc. This was to be followed by the second two years involving the actual demonstration of three H_2 buses and running a commercial infrastructure. The general scheme of the project is shown in Figure 1.

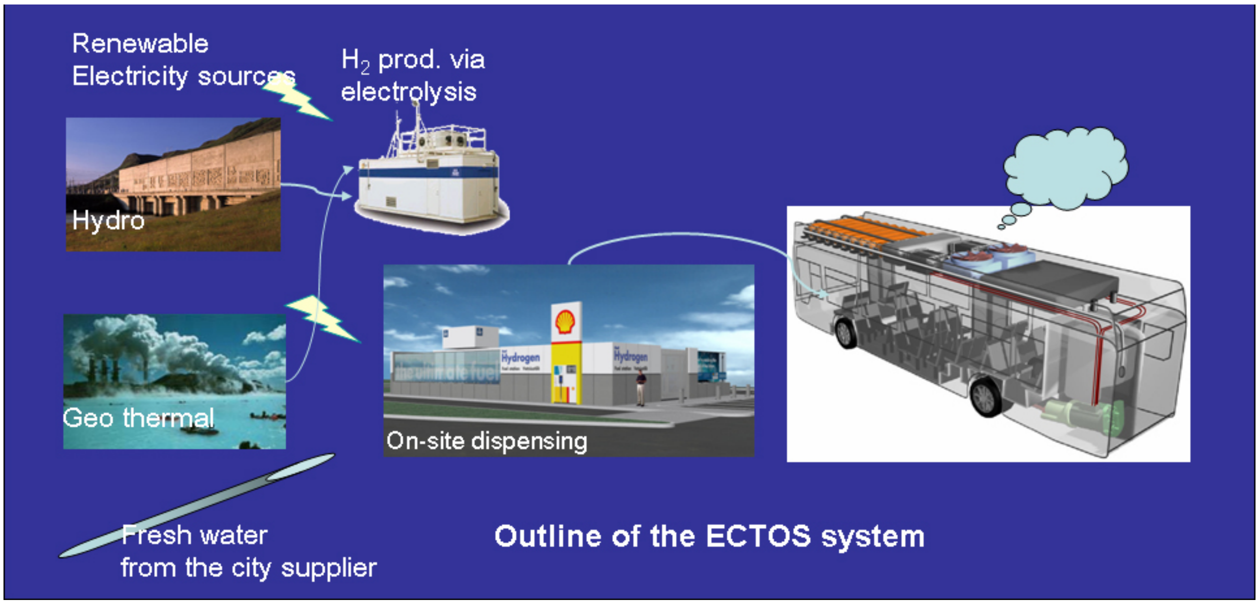

Figure 1: Outline of the ECTOS system

The infrastructure preparation involved building a hydrogen production, compression and refueling station integrated into a Shell facility on the outskirts of Reykjavik. The station is equipped with a Norsk Hydro alkaline electrolyser operating on the municipal power grid and with a connection to the municipal water network. It can deliver gaseous hydrogen after compression at 44 MPa (440 bar). Refueling a bus with around 30 kg of hydrogen is slowed down to take about 10 minutes. The total production capacity at this stage of the station is about 200 kg/day.

Three Fuel Cell Citaro buses from Evo Bus, a daughter-company of DaimlerChrysler, were delivered to Iceland in August – December 2003. They are powered by gaseous hydrogen at 35 MPa (350 bar) pressure stored in the front roof section. The fuel cell system is also situated in the roof structure of the bus. The fuel cell is a 250 kW PEM system from Ballard, with an expected driving range from 150-240 km on each filling of hydrogen fuel, depending on the number of stops and idling time. The buses have been operated since October 2003 on normal routes within the Reykjavik public transportation system, and the hydrogen filling station has been operational since April 2003. The bus drivers fill the vehicles daily; their route is approximately 180 km during one shift that lasts 7-8 hours. In order to avoid freezing in the fuel cell system overnight, the buses are either parked inside or warmed during the night by electric power from the municipal grid, and the temperature is monitored with a remote reader.

An additional important ingredient of the ECTOS project is the analysis of driving forces and hurdles for a hydrogen economy in Iceland. The University of Iceland and Mrs. Maria Maack are responsible for socioeconomic analysis and a number of surveys intended to watch the development of the public acceptance of the new concept. In 2001, shortly after the kick-off of the ECTOS project, yet two years before the driving tests were launched, a poll was conducted of a group of 1200 Icelanders who were asked about their knowledge about Icelandic New Energy (INE), the promoter of hydrogen in Iceland. Only 23% said they had heard of INE. When asked about their attitude towards hydrogen as an energy carrier, 93% said they held a positive stance. This figure was unexpectedly high and points towards an unusually positive public opinion, which may prove difficult to keep at such a high level.

A Life Cycle Analysis (LCA) for the equipment and the fuel chain was conducted, i.e. a well-to-wheel analysis (WTW), as part of the ECTOS project. This was done to benchmark the character of the first system, using prototypic hydrogen equipment. This investigation was performed in close cooperation with the Institut für Kunststoffprüfung (IKP) at the University of Stuttgart.

The cross-sectional and cross-cultural organization, combining the micro company Icelandic New Energy (INE) and the three international companies, has been very successful. The know-how accumulates within INE but new projects sprout from merging the ideas of many experts in other fields of energy and technology throughout national and international collaboration. 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, but many spin-off projects have already been established.

3. DESCRIPTION OF COMPONENTS

3.1 Hydrogen refueling station

A major milestone towards the introduction of hydrogen was the completion of the first hydrogen electrolytic station designed to produce, compress and dispense hydrogen gas fuel *in situ*. The water from the city's water-network needs very little treatment as it contains unusually low concentration of any minerals. The station, which is pictured in Figure 2, was planned, designed, tested, erected and inaugurated by April 2003. Norsk Hydro delivered all the components while Shell Hydrogen and Skeljungur in Iceland saw to the external design. It has been safely operated for over two years. Parts of the station equipment have been changed and redesigned during the test period.

The hydrogen refueling station consists of four major components (as indicated in the picture):

1. Production unit including gas purification, and cooling tower
2. Compression unit,
3. Hydrogen storage including valve distribution panel and
4. Dispenser

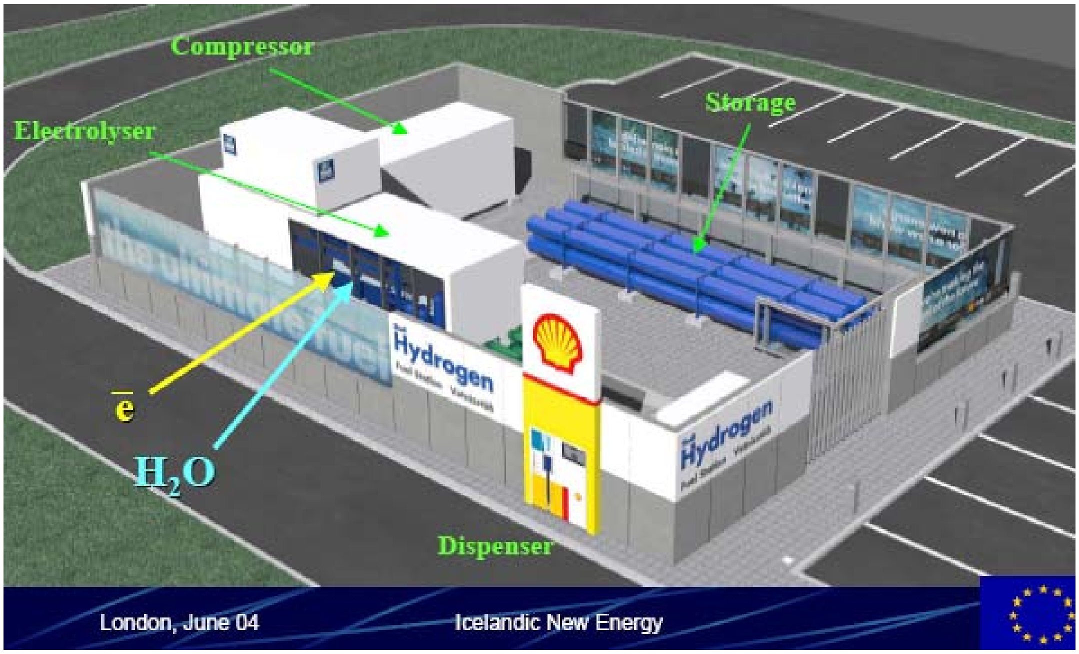

Figure 2: The Icelandic hydrogen refueling station

In the electrolyser, the gases are generated at a pressure of 1.5 MPa (15 bar) and a capacity of 128 kg hydrogen/day (60 Nm^3/hr). Oxygen is vented to atmosphere. To operate the electrolyser, a DC supply is required. A specially designed transformer is necessary to step down the incoming AC voltage to accommodate the required input voltage for the rectifier. This is necessary for electrolyser operation.

The gas purification equipment, located downstream of the electrolyser, consists of a deoxidizer and a twin tower dryer. These are included in order to remove traces of oxygen and moisture in the gas.

Figure 3: Containerized electrolyser package producing 60 Nm3/hr at 1.5 MPa

The containerized electrolyser unit shown in Figure 3 includes purification and drying equipment. The container is 9 m long.

A high-pressure compressor is included as a complete skid-mounted package to ensure safe and reliable operation. For the refueling station with storage pressure of 44 MPa, an oil free diaphragm compressor is selected.

Downstream of the compressor a gas storage system is included. It comprises three independent storage banks to provide a three-stage decanting system to ensure that the bus storage tanks reach the predetermined pressure without exceeding 85°C. To achieve this goal, a mathematical model was constructed and verified by experimental data. The pressure and temperature build-up for a simulated refueling is shown in Figure 4.

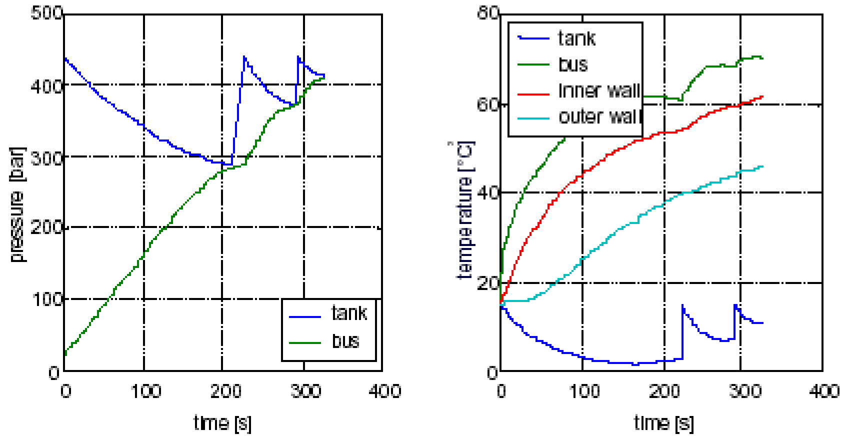

Figure 4: Temperature and pressure build-up with the 3-bank storage system

Maximum utilization of the storage volume and the three-stage decanting sequence system is provided through a hydrogen fuel distribution panel.

A fuel gas dispenser transfers high-pressure gaseous hydrogen from the fuel station storage banks to the storage tanks on-board the vehicle. The fuel gas dispenser, similar to a conventional fuel pump, is the mechanical interface between the hydrogen fuel station storage banks and the vehicle. Safety features and metering equipment provide safe and reliable operation. The dispenser unit also has it's own Programmable Logical Controller (PLC) unit, to provide metering of the hydrogen gas fuel supplied to the vehicle, pressure monitoring and communication with the refueling station control system.

The first dispenser installed at the station had communication problems with the vehicles and the pressure of 35 MPa could not be reached. The dispenser was substituted in early 2004 by a new type of dispenser developed by the Norsk Hydro team. After the installation, the filling has not posed any further problems. The temperature of the hydrogen rises during filling and therefore expands. The dispenser communicates with the vehicle sensors and the refueling procedure is slowed down automatically to not overload the system with too high pressure.

The plant is delivered complete with an integrated PLC system for safe and unattended operation. Necessary gas quality analyzers and gas detectors are included. The operations are monitored through a computer system and the process can be remotely controlled. UV detectors watch out for hydrogen flames and would give a sound alarm in case of leaks.

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’. On the station, both the function of an electrolyser and that of a fuel cell are explained in simple terms and drawings. The texts are both in Icelandic and English. The light, transparent walls that surround the station allow people to see the various components of the station.

Actually building the first fuel station within the ECTOS project became a practical training lesson. It took a longer time to find an acceptable location for the hydrogen station than actually to build it. The site selection demanded close collaboration of the local oil company Skeljungur, Shell Hydrogen, and the planning department of the municipality of Reykjavik. 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 Icelandic public.

3.2 Fuel cell buses

Results from the NEBUS, the first Mercedes-Benz fuel cell bus, had shown that the fuel cell itself was not necessarily decisive for the vehicle availability and for the fuel efficiency, but in fact the various auxiliary units played a decisive role in many cases. From the start of the development phase of the Fuel Cell Citaro, special attention was therefore given to maximizing the use of series-production components in order to achieve a high availability of the entire drive train.

For this reason it was decided to develop the fuel cell drive train based on the conventional Mercedes-Benz Citaro, employing, in addition to the main components such as alternators, compressors etc., also the standard automatic transmission, while being aware that this might have negative effects on the vehicle fuel economy.

The Fuel Cell Citaro is based on the 12 m series vehicle of Evo Bus, which features a standing platform in the left rear area for placing the engine as well as an automatic transmission. The body shell of these vehicles was reinforced especially in the roof area due to the three extra tons of load for the fuel cell drive train and the air conditioning system. The suspension was adapted to accommodate the higher weight and shift in the balance due to the weight on the top.

No modifications to the entirely low floor construction and the door concept were necessary. Also the outside dimensions remained unchanged except for the vehicle height, which is approximately 3.70 m due to the fuel cell drive train and the fans of the cooling module. The Citaro bus is shown in Figure 5; the technical data given in Table 1 describe the vehicle comprehensively.

Table 1: Characteristics of the fuel cell Citaro bus

Overall length		12.00	m	
Overall width		2.55	m	
Overall height		3.67	m	
Turning diameter		21.5	m	wall to wall, equivalent to conventional diesel CITARO
Weight	empty	14.2	t	
	loaded	18/19	t	depending on country
Passenger capacity		< 70		

The HY-205 P5-1 engine is the fifth generation of heavy-duty drive trains developed by Ballard of Vancouver (Canada). It was designed around the newest Mk9 stack technology to efficiently convert gaseous hydrogen fuel and atmospheric oxygen directly into electricity and water. The electricity is fed to a compact but powerful liquid-cooled electric motor, which provides the bus traction and also drives the fuel cell engine auxiliaries and the bus auxiliaries through a central gear case. Several separate liquid systems are installed in order to cool the equipment and to provide heat towards the interior of the bus.

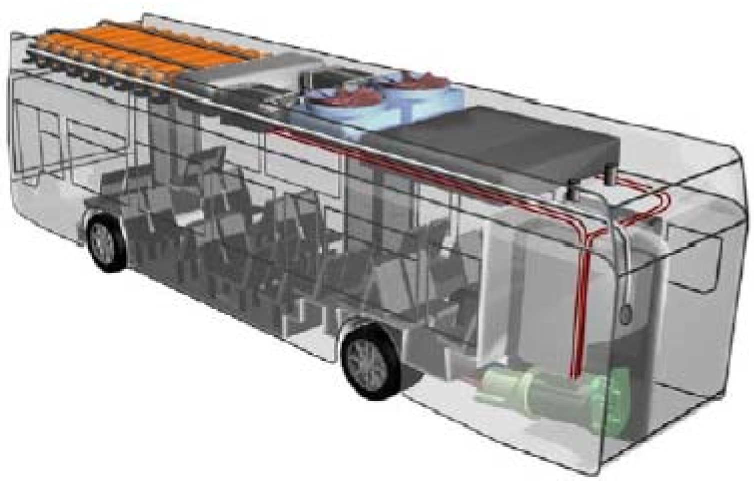

Figure 5: The DaimlerChrysler Citaro bus

The P5-1 fuel cell engine design and architecture focus on reliability and durability by using as many industrial off-the-shelf auxiliaries as possible. The drive train arrangement in the vehicle addresses European safety regulations and standards. It is designed to enable a direct replacement of a diesel drive train commonly used in bus applications. The electric motor module has conventional mounts and an industry standard (SAE 1) transmission flange. It can be mated to any suitable automatic transmission and differential to provide a reliable vehicle traction system with excellent hill-climbing ability, fast acceleration and high road speed. The electric motor operates continuously from an idle speed of about 600 rpm to a maximum of about 2,100 rpm.

The main systems and functional groups of the HY-205 fuel cell drive, as well as their main specifications, are shown in Table 2. These modules are integrated packages with defined fluid, electrical and mounting interfaces. They are connected with each other, and to the bus, with interconnection piping and power-wiring systems. In addition to the main units, the hydraulic pump circuit and lubrication oil circuit are powered by the auxiliary gear case. The 24 V_{DC} supply is provided by three belt driven alternators, which are also driven by the auxiliary gear case.

Table 2: Fuel cell engine specifications

Emissions	CO NOx hydrocarbons SO_2 particulates CO_2	0.000 0.000 0.000 0.000 0.000 0.000
Performance	net shaft power at 2100 rpm peak torque at 800 rpm	190 kW 1050 Nm
Fuel	gaseous hydrogen at ambient temperature supply pressure required flow fuel purity of hydrogen from the electrolyser fuel purity after drying	 ≥ 1 MPa (10 bar) ≤ 0.005 kg/s 99.8 % 99.9999 %
Tank capacity	in 9 pressure cylinders at 35 MPa	≥ 40 kg
Range		200 km
Maximum velocity		80 km/h
Air	two stage compressor; flow rate (max)	0.3 kg/s
Cooling system	water/glycol cooling loop with coach heating interface	
Temperature	fuel cell operating ambient operating ambient storage without freeze provision ambient storage with freeze provision	70 to 80°C -20 to +40°C 2 to 50°C -20 to 40°C
Pressure	system operating (nominal)	0.2 MPa
Electric power	fuel cell voltage range liquid cooled IGBT inverter integral ground fault detection	550 to 900 V_{DC}
Dynamic braking	supplied by transmission retarder	
Transmission	6 speed automatic transmission	

A summary of the traction module characteristics is given in Table 3. The same type of bus and fuel cell system has also been used in nine European cities within the CUTE project (Clean Urban Transport for Europe), in the STEP project in Perth, Australia, and in Beijing. More information on the bus and on all the subsystems may be found in the report "Hydrogen Supply Infrastructure and Fuel Cell Bus Technology", which is available at www.fuel-cell-bus-club.com.

Table 3: Traction module characteristics

General output	nominal motor output	250 kW shaft power
	capacity	340 kVA
	rated output current	450 A (1200 VDC IGBT)
	maximum output voltage	3-phase, 460 V or 0.7 x DC input voltage, whichever is less
	rated output frequency	400 Hz (max) at full torque
	overload capacity	150 % rated current / 1 minute
	PWM frequency	between 2.5 and 5 kHz
Control power supply	voltage range	14 – 35 V
	load rating inverter	6 A (maximum)
Main power supply	input current	425 A continuous,
		540 A maximum for 5 minutes
	rated voltage	600 VDC (full load) to
		900 VDC (zero load) input

3.3 Maintenance Facility

The maintenance facility had to meet all safety criteria set by the authorities. If hydrogen is trapped within a building there is always the risk of explosion or fire and there may be a risk of amnesia if the concentrations become extremely high. Also, because the buses are taller than most diesel vehicles, the ordinary maintenance bays did not fit the hydrogen fuel cell buses. In some instances, the maintenance team would choose to work on the maintenance outside and avoid trapped hydrogen by skipping the roof (as is the case at the fuel station). But given the climate in Reykjavik, the outdoor solution was not considered good enough.

The maintenance bay was therefore situated inside the garage of the milk factory in Reykjavik, which is located just 200 m from the hydrogen station. Its doors are about 3 m tall. A specific pipe that leads through the roof of the building is connected to the hydrogen container units on top of the buses. In this way any leak of hydrogen is vented immediately outside and diffuses to the atmosphere. Also, two very sound stand-alone staircases had to be purchased because much of the maintenance work is performed on the bus roofs, 3 meters above the ground. A suspended safety swing is also provided for the maintenance team to keep them secure during their work.

4. PERFORMANCE AND OPERATIONAL EXPERIENCE

4.1 Refueling station

During the two years of operation several problems were detected. Firstly the combination of using pressure, lye and hydrogen has proven to be very aggressive on the selected material at the station, namely high-grade steel. Any carbon traces in the material, especially in combinations at welding points and bends in the pipes, must be monitored during the use phase. Therefore the control and maintenance proved to take a higher toll of the budget than expected. A few points of the original design have already been changed and during the first year of operation several stops were enforced for safety reasons during surveillance times. The first dispensing unit also had to be replaced for a Norsk Hydro branded dispenser. An incident occurring in August 2004 is described in more detail below.

Since December 2004 the operation has been absolutely satisfactory. Therefore the main goal of the whole ECTOS establishment has been achieved – namely it has taught the participants lessons, which have been incorporated directly in the operation and given indicators for the design of the next generations of electrolytic stations.

It can be quite tricky to obtain static data through the monitoring system. Every time the bus hydrogen tanks are filled, the readings for temperature, pressure and weight fluctuate. Not as if that was unexpected, but it makes all data processing rather complicated if the data are to be read from the monitors at the station. For plotting and simulation purposes the monitoring computer has therefore come in very helpful; the data are downloaded on CDs every time the station is shut down and the data have been made available for the ECTOS project, even though the findings should be considered commercially sensitive. The IEA Hydrogen Implementing Agreement Task 18 has undertaken some analysis of the data.

A specific feature of electrolytic hydrogen production stations should be mentioned. Every time that the electrolysing equipment is turned off (be that for control purposes or during weekends when bus drivers are unavailable and therefore no hydrogen is being purchased), the production unit needs to be flushed with inert gas, namely nitrogen. If the electrolyser is simply shut down then the hydrogen within the system can attack surfaces and damage the equipment. However, using nitrogen to drive out the excess hydrogen and water steam is yet very costly. Therefore it is more economical to produce hydrogen throughout prolonged periods of time rather than to shut down the process when the demand decreases. Adding two or more H_2 vehicles to Reykjavik's fleet would therefore make the operation more economic. Later generation of high pressure electrolytic stations will be kept under pressure during down periods and thus oxygen prevented from entering the system without any flushing.

4.1.1 Incident

In August 2004, during startup of the station, one of the pipes actually gave away and the pressure dropped. Fortunately the operational staff was not injured as the blow happened in the electrolyser compartment but the startup is performed in a specific monitoring compartment at the station. A pipe had blown up at a typical vulnerable bend. A task force was formed incorporating representatives from the producer, the operators, Icelandic New Energy and an outside expert. The plant was kept down and the buses were parked until the task force report was issued, even though operation would have been possible after a simple exchange of the damaged pipe. The reasons for the incidents proved to be a level transmitter malfunction, manual override of the control system during startup, and a missing demister. The last item was probably a failure during the manufacturing.

The repair process included a change of all H_2 pipes between the separator and the cooler. The position of a pipe lying between the electrolyser and the purification system was changed and redesigned. The material in the pipes that contain hot lye during operation was upgraded. The level transmitter was replaced and the missing demister installed. The interfaces for the operators were also revised, the electrolyser control updated, and the staff trained to comply with the new operational procedures. Finally, before the start up of the plant after repairs and some redesign, the Hazard Operational Plan was revised and a new hazard management scheme implemented.

In the end the lessons from this incident became very valuable for both the manufacturer and the operator. The way to tackle the incident in an open fashion and take time to analyze it in details made the lessons all the more valuable. Therefore, running the station in a pre-commercial mode and testing the operation during a two-year period proved to be essential.

4.2 Fuel cell buses

The performance of the Citaro FC buses has exceeded all expectations of reliability. From the start of the test drives the buses have been operated successfully for 90,000 km without any major changes or replacements. The overall availability was 93.1%, and a summary of the operation statistics is shown in Figure 6. The passengers show pleasant reactions and the drivers have been happy to participate in the demonstration. They report that the buses are much more advanced than they expected, accelerate quite well, are stable on the street, and tough dealing with snow.

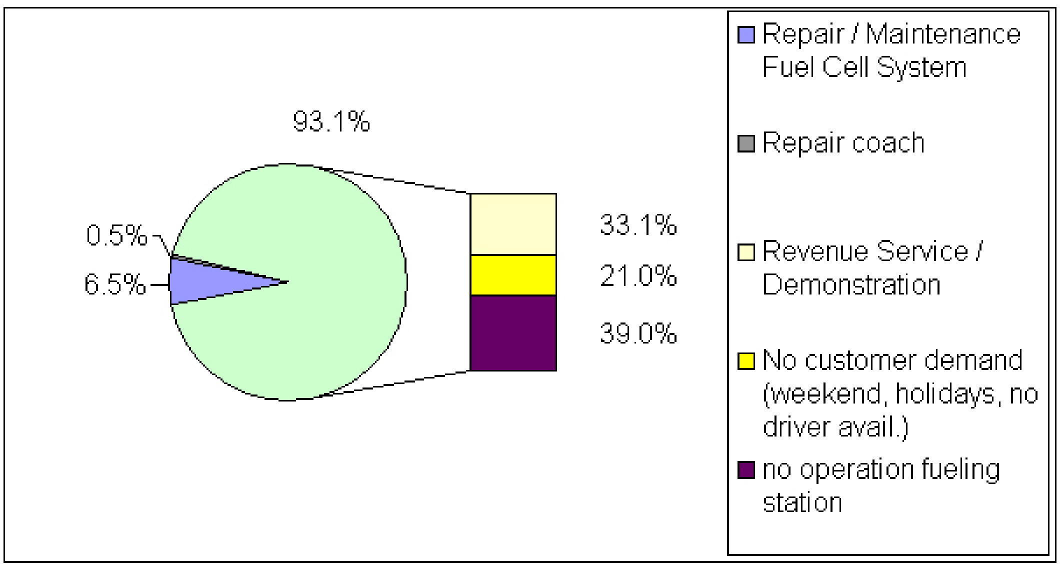

Figure 6: Overall availability of the Reykjavik buses from April 2004 through March 2005

Of course problems were met at the beginning. First the warning mechanism and the software proved to be too sensitive to fluctuations in the total system, showing red alarm so that the bus drivers had to call in the alarm team. Most of these signs were not serious and the alarm system was monitored to become more tolerant to small variations such as in air humidity. As soon as sensors were insulated well enough and the cooling system made to operate more efficiently, then the problem was overcome.

Early in the demonstration phase a cooling loop failed. A hose became disconnected from a pipe containing cooling liquid and a cloud evaporated from the top of the bus. The smell of glycols spread from the vehicle, alarming the passengers. Neighbors called the fire brigade and the police. They closed the surrounding streets but these service teams were not well informed how to react until the maintenance staff arrived, only to put the hose back on and drive the bus away.

This became a valuable lesson for the authorities, regarding incident reaction. Their representatives volunteered to have a meeting with INE to learn about alarms and safety measures, something that had been offered earlier without success.

Some electronic spare parts and new valves on the fuel pressure tanks did not operate perfectly at the start of the test drives. Problems related to spare parts, logistics and difficult import / export rules in Iceland were to blame for most of the stoppages during the first 6 months. All spare parts were of course marked as equipment for hydrogen bus and therefore classified as hazardous chemicals. The delaying procedures were discussed with the experts on import taxes and customs at the ministry of finance. In a joint meeting it was decided to make up a new import code for the spare parts and separate it from the class of hazardous material and chemicals. This finally sped up the import procedures and probably also facilitated the passing of a new law during the spring of 2005 which reduced the taxes on vehicles and equipment for reduced emission.

Amongst the learnings from ECTOS and CUTE is that even though the auxiliary equipment has been used successfully for other drive trains, the energy economy may be raised considerably if the systems were to be adapted specifically to the Fuel Cell drive train. Energy is lost during conversions that feed power into the various subsystems. Much has been done to boost the fuel economy and reliability of these pre-serial buses. The fuel economy has increased during the test period, but it is mostly with the next generation of buses that new developments will be integrated.

4.3 Social benefits

As the tests have been monitored extensively, several additional benefits have been registered. Since the establishment of Icelandic New Energy, the largest international media such as BBC, NBC, Reuter and the Deutsche Welle have covered this story in their news. Articles on the project have appeared in *Der Stern*, the *Guardian*, *Newsweek*, *The Economist* and the *Red Herring*. Korean, Swiss and Austrian agents have made documentaries. Since the establishment, the number of visitors at INE amounts up to 2000 people and therefore it can be stated that hydrogen tourism has brought quite some income for the Icelandic economy. The company directs this interest towards seminars on the hydrogen initiatives, which are commonly offered by the University of Iceland and INE.

A second interesting feature appears when the maintenance and material bookkeeping is studied. When the hydrogen buses arrived in Reykjavik, two new diesel buses were also taken into the city's bus fleet. It turns out that the gear oil and motor oil have been changed twice in the diesel buses but never in the hydrogen drive train. Therefore using the hydrogen buses instead of conventional diesel buses in the local traffic has saved about 350 kg of motor oil and grease. On top of that, the amount of CO_2 avoided is about 150 tons.

Thirty drivers have been trained to operate hydrogen buses. Specialized staff has also been trained to operate and maintain the station and the fuel cell systems, the first people to gain this experience in Iceland. School groups and interest groups have visited the facilities by the dozens and during the summer of 2005, the first group of teachers from vocational schools attended a training course hosted in a fuel cell laboratory in Germany. Chapters have been issued in the school curricula on hydrogen and the latest technology. Therefore it can be stated that the ECTOS project plus other initiatives have made a remarkable social impact.

4.4 Routes and working plans

In the beginning, the buses were mainly driven on selected routes and the plan was to keep them in the traffic during whole days (14 – 16 hours). But for simple logistic reasons this became too complicated and time-consuming for each driver and therefore too costly for the bus operator. The fuel cell buses cannot be cleaned in a normal bus wash and the bus-drivers had to wait their turn, sometimes several hours after their normal 8-hour shifts, until all the milk-vans had had their turn in the cleaning facility at the milk factory. Therefore it was soon decided to use the FC buses during one shift per day and have one driver as a go-between between the licensed drivers within the group and the hydrogen-bus services. He then filled up the hydrogen tanks and brought the FC buses into the traffic wherever the appropriate drivers were working during their shifts. In this way the buses could be kept driving during the entire shift, but the drivers did not need to follow the bus through all the stages during the extra services, whether that was regular maintenance or checkup, filling the fuel or adjustment of any of the equipment.

On top of smoother system operation, this change had the advantage that the buses showed up in all parts of town. The inhabitants of the city got equal opportunity to see the buses in action in their vicinity, and they never knew beforehand if they would get a ride in a hydrogen bus or in normal diesel vehicles from their local bus stop!

4.5 Monitoring the fuel economy

The storage bottles on top of the buses keep the hydrogen gas at 35 MPa pressure; refueling takes about 10 minutes. The temperature rises during the filling of the storage containers but the dispenser is equipped with a pressure sensor that monitors the filling, communicates with the monitor in the hydrogen station and keeps the fuel flow within proper pressure ranges. The daily fill of hydrogen (around 45 kg) allows the buses to drive 150-240 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 specific fluids in closed loop towards the bus interior and the temperature is regulated automatically. The specific air conditioning and cooling system for the interior that is a standard feature of the Citaro fuel cell buses from Evo Bus was not often needed in Reykjavik.

While running hydrogen through a fuel cell, water is of course being produced. Some of it becomes steam and leaves the system quite easily, as seen at the steam vent at the back of the bus. Yet, because PEM cells are sensitive to high heat the cell stacks must be cooled down. Therefore the byproduct from producing the electricity will always partially turn into liquid water that can accumulate in the stack and slow down the process. This can happen during idle times or at full speed. Therefore all PEM cells need a mechanism that clears the stacks once in a while or else the electricity production will be slowed down. As the goal of the design for the Citaro fuel cell stack was to optimize the reliability of the bus, some of the fuel economy was sacrificed compared to the older NEBUS system from DaimlerChrysler. The equipment pushes hydrogen more rapidly through the stacks and purges away excess water. To dilute any hydrogen that may escape the system it is mixed with atmosphere in a specific vent on top of the bus, wasting some of the precious gas in order to keep the system smoothly running.

It is generally known that cold starts for fuel cells can be difficult and temperatures below freezing point can damage them. Problems with cold starts have, however, not been reported but it does take longer time to get the fuel cell going on very cold mornings. Thermometers with remote readers were installed especially in the Reykjavik FC buses so that the night watch might read the actual temperature during the night and call out for service if the temperature was sinking towards zero. Thus the staff at the maintenance shop was always ready to get the fuel cell started during cold spells and to prevent any damage to the valuable equipment. However the climate is not as cold in Reykjavik as people may anticipate; the average winter temperature is about 0°C. The dairy trucks, which run on diesel fuel, are always connected to motor heaters while they are idle during the night. This is a normal procedure in many companies in cold climates. The risk of freezing was taken into account in Reykjavik already during the first driving season. Therefore, instead of taking chances to have the sensitive and expensive FC equipment suffer from freeze damage, the hydrogen buses are now parked indoor during the night after several cold spells during the winter months. This keeps the equipment above the freezing point at all times and boosts the fuel efficiency of the vehicle.

Soon after the bus demonstration was launched, the AC/DC inverters of the buses were changed. The first model did not stand up to their task; they overheated and failed. The second generation of inverters has shown good results, but inevitably quite some energy is lost during transformation of the current to make it compatible with the AC auxiliary systems.

5. ENVIRONMENTAL ASPECTS AND SAFETY ISSUES

5.1 Hydrogen Refueling Facility

Safety aspects are given great attention within Norsk Hydro for the design and construction of the refueling station. Norsk Hydro, along with Det Norske Veritas, is actively participating in a number of ongoing international projects to establish practical standards and safety guidelines for refueling station design. In general, care is taken with regard to location of hydrogen equipment, relative to source of fuel including pipelines and bulk storage flammable gases and liquids. All equipment is selected for simple and safe operation and maintenance. In addition, all equipment is readily accessible for fire fighting services, and easy means are provided for escape of persons in the event of an emergency.

The electrolyser and compressor are delivered in two separate containers. The safety concept is based on IEC 60079-10 for zone classification with all the equipment used, certified for applicable area as shown in Figure 7.

Figure 7: Containerized electrolyser without wall panels showing the electrolyser unit separated by a wall into hazardous and non-hazardous area.

The European Industrial Gases Council IGC has provided guidelines for compression, purification and storage of hydrogen. This document IGC 15/96 E/F/D together with NFPA 50A have been used for determining safety distances.

Both the electrolyser and the compressor container are equipped with a double fire detection system consisting of UV and smoke detectors together with gas leakage detectors in hazardous areas. The complete refueling station, excluding the dispenser, has a fence around to limit public access because of the risk of building up static electricity in the vicinity of the electrolyser.

Outside the station walls, a distance of 13 m is maintained as a zone free of obstacles. But a normal petrol 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.

It is not enough to have the single units all according to codes and standards, but the whole system has to be checked for health and safety hazards. All connections and external design have to follow the simple guidelines that lead to a safe operation, avoiding leaks, damage from incorrect household procedures etc. Therefore all work follows prescribed procedures according to the operational handbook and plans for risk assessment, emergency plans and health safety and environmental rules. A hazard operation plan has been established involving all the key people in the INE staff.

5.2 Fuel cell buses

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 flash and the bus driver is obliged to contact the maintenance staff 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 its proper operation, 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; salt particles from the sea often interfere with electricity transmission on the national grid, even far inland. Yet no interference or disturbances could be observed from the salty winds during the test period. The bus carries most of the hydrogen equipment on the specifically strengthened roof. In case of any leaks, the hydrogen will rise and diffuse quickly into the atmosphere.

5.3 Impact on air quality

A list of scenarios considering various proportional penetrations of hydrogen on the market and the expected decrease of air pollutants is displayed in Figure 8. It is generally accepted that fuel cell vehicles will most likely serve initially as an option within public transport. For the time being, the fuel cells and hydrogen containers are bulky and need much space unless the pressure is raised considerably. However, they can replace buses that use diesel oil as a fuel and give rise to unhealthy air emissions in urban areas and also to the emission of 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 converted to widespread hydrogen usage.

The forecast of changes presented in Figure 8 is based on measurements within ECTOS and the composition of exhaust from buses and other vehicles in Reykjavik. In the outset (Scenario 1) it is stated that all buses and 50% of the trucks already drive on hydrogen but which changes are to be expected if the ‘hydrogenisation’ goes even further to incorporate private vehicles as well ? Normally most air pollution of CO_2, CO, hydrocarbon residues (HC), nitrogen oxides (NO_x), sulfur oxides (SO_2) 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 personal vehicles and they tend to prefer even large models; hence the large changes in emissions of CO_2, NO_x and CO are forecast.

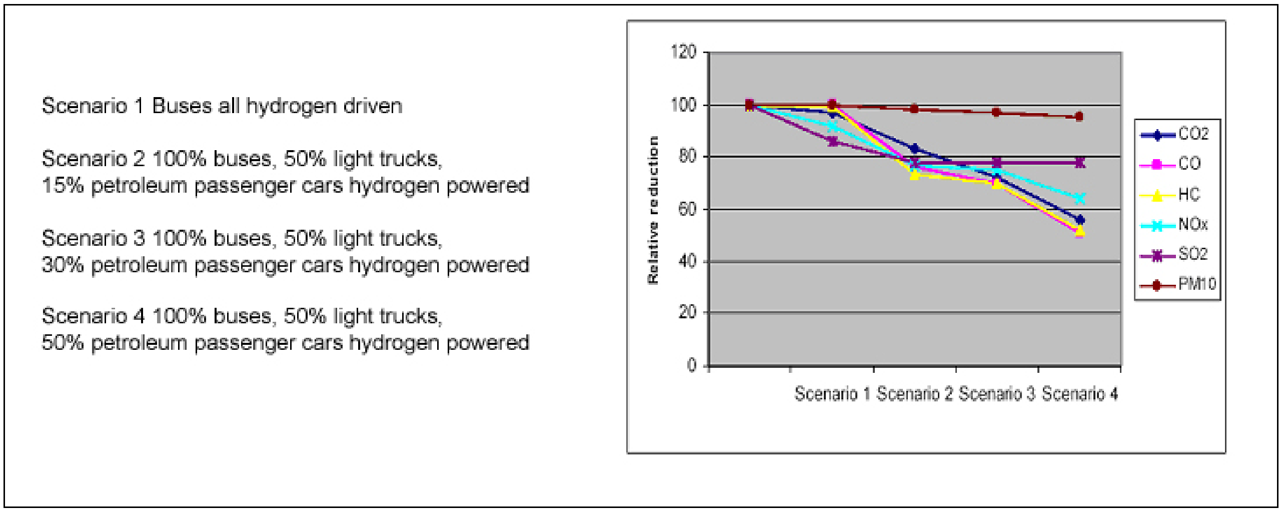

Figure 8: The expected changes in air quality in Reykjavik compared to various scenarios for Hydrogen penetration on the market. © Icelandic New Energy

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.

Within the ECTOS project, a Life Cycle Assessment (LCA) of the impacts of using the new hydrogen technologies in Iceland has been conducted[1]. The largest impacts will be the ones inflicted during the operation phase of the vehicles, but because of the unusually low emissions to the atmosphere from the hydro and geo-thermally 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 sulphur compounds from geothermal vents in high heat geothermal areas[2].

Specific technological methods exist already to trap these emissions at the source. In the end, the emissions from transport and the fishing fleet should be cut by almost 90% if hydrogen becomes the energy carrier for these sectors. The expected changes in air pollution in Reykjavik depend therefore also on other measures.

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1 Skuladottir Bryndis, H. Thorisson (2004) ECTOS *Environmental evaluation of air quality, midterm report.* Available in English online at www.iti.is

2 Mailänder, Ellen (March 2003), *Life Cycle Assessment (LCA) of Hydrogen Infrastructure for Fuel Cell Driven Buses in the Public Transport of Reykjavik*, Institut für Kunststoffprüfung und Kunststoffkunde, Universität Stuttgart

6. REGULATORY ASPECTS AND LICENSING PROCEDURES

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. Eventually, the Icelandic authorities accepted that the same rules for safety, health and hazard management would apply as in Germany, where the buses are built and tested, and in Norway where the hydrogen station is composed. Therefore standards and handbooks from the German safety authority TUeV were adopted for the buses, along with procedure descriptions from Det Norske Veritas, who have been collaborating with Norsk Hydro.

It was, however, essential for this information to be available in Icelandic before further development could occur. Shell Hydrogen has provided very valuable guidelines for the Health-Environmental & Safety management at the station. Invitations to the Institute of Standardization and Energy Controllers to all educational events on hydrogen handling also became a standard procedure on behalf of Icelandic New Energy.

Part of the homologation procedures was to train drivers for the right responses to alarms within the bus system. A few simple rules were pointed out in posters that were hung up inside the buses.

7. EARLY INDICATIONS OF PUBLIC ACCEPTANCE

Various approaches were used to collect data within the socio-economic and environmental research in ECTOS. These projects 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.

The first public survey was made in December 2001 to serve as a standard reference for later tests on the social acceptance. The Institute for Applied Sociology of the University of Iceland performed a telephone survey and asked 1154 people about issues related with hydrogen. This outcome was more positive than expected, whereas the public was reputed 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 project, 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 main results are the following:

- A vast majority of the respondents, 92%, claimed to look positively or very positively upon the tests that are now made with hydrogen as fuel.
- 86% of the respondents claimed to be positive or very positive towards the development of using hydrogen as the main fuel for buses, cars and vessels.
- 36.5% of the respondents say that the price for hydrogen may be set higher than that of gasoline during the introductory stages.

- 78% of respondents claim not to notice change in the level of noise between the fuel cell buses and normal city buses.
- A vast majority of the interviewees connect the concept hydrogen to neutral or rather positive phenomena such as water and clean environment but less than 3% to negative thoughts such as explosions.
- 48.5 % regard hydrogen to be a safe energy-carrier
- 45.5 % of the respondents claim that the tests have not been introduced enough to the public.

Results of surveys, preferences, technical performance, costs, etc will later 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. ECTOS is a fine base for further studies. All these pieces of information are helpful to decision-makers that need to plan for a sustainable energy system, which suits common goals and social development.

The reports will be presented to key persons within governmental bodies in 2006 so that the people that 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.

8. ECONOMIC CONSIDERATIONS

The Reykjavik hydrogen Shell station was tailor-made to fit its applications within ECTOS and become a good representative for the emerging hydrogen technology. The station cost approximately 1,000,000 EUR 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 prices offered are the same as for any other small user[3]. On the other hand it is expensive to store and transport hydrogen, both as a gas and as a liquid. The price for land for storage is rather low in Reykjavik in an international context but can also become an influential factor in the fuel price because of the bulky nature of hydrogen or due to imposed security zones. Until 2006, the actual figures for the operational costs will only be used internally for the partners of the ECTOS project: The local oil company Skeljungur is responsible for the operation of the hydrogen station.

The costs for hydrogen will be calculated based upon all the parameters that were tested during the ECTOS demonstration. However, they will not be representative for the costs of hydrogen in the future because the 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, of the bus design with its auxiliary components etc. will be different from the system that is currently being tested. This indicates that the investment cost that went into the ECTOS

[3] Frisbaek F. (2004), Masters thesis for the degree of MSc in Energy Engineering at Danmarks Tekniske Höjskole; *Euro-Hyport final report, infrastructure for the hydrogen economy*.

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 approximately the same for running a bus on taxed diesel fuel and hydrogen, provided that the electricity price is set at 5 eurocents per kWh. No investment cost or maintenance cost is incorporated for neither the diesel nor the hydrogen buses, and the infrastructure is not included in either drive train. Only during the test drives, the equipment of the fuel cell buses has been streamlined to show about 15% better fuel economy than during the first stages. Also there is a vast difference between the fuel consumption during long distance driving and normal public transportation where the buses stop every 2nd minute. 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[4] with the costs of using one prototype hydrogen station that offers services for only three vehicles.

At the beginning, the goal was eventually to offer hydrogen for 120% of the price of normal fuels. In other words a passenger should expect that the price of traveling a specific distance would be 20% more expensive if she was using hydrogen compared to other fuels on the market. Yet, during only the past few semesters the rise in oil prices has been about 40% in Iceland - if this tendency continues then the price will soon become the same for taxed diesel oil and untaxed hydrogen.

9. REMARKS ON FUTURE POTENTIAL

The ECTOS project is still only a forerunner for further tests and demonstrations. The realization of a hydrogen economy has yet been pushed forward through the outcomes. The project has shown that a hydrogen public transportation system based on electrolysis and fuel cell drive train is possible and reliable and the hurdle of high investment costs can be overcome.

One feature that has become evident during the ECTOS project is that a considerable amount of energy is lost from the tank–to–wheel due to the non-compatibility of the fuel cell formation of electricity and the auxiliary equipment that runs on AC current. Too much energy is lost as heat within the inverters. A second generation of buses will have new energy saving features to the drive train. It is clear that they will be hybrid vehicles with one or several new features such as small electric motors for each wheel or equipment that uses saved energy from braking to accelerate the vehicle, better energy deliverance through more appropriate features within the electricity transformations or super capacitors. The car manufacturers will more or less integrate this type of new technology into most vehicles in the near future, but which ones become the standard equipment for fuel cell buses is not clear at this stage.

[4] Ogden, Joan, R.H Williams, E. D.Larson *Societal lifecycle costs of cars with alternative fuels/engines.* Energy Policy, (Jan 2004, Elsevier)

10. CONCLUSIONS

The results of the ECTOS project are very promising. As of August 31, 2005 (formal end of project) the vehicles have

- covered 89,243 km in 5,216 operating hours,
- pumped 17,342 kg of hydrogen,
- saved over 58,000 l of diesel, and
- reduced the greenhouse gas emissions by more than 150 tons.

More than 90% of the public admit a positive or very positive attitude towards hydrogen fuel.

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 applications and the hydrogen initiatives indicates that the rest of the world is intrigued. Professor Bragi Arnason, a true visionary for the local hydrogen economy, has stated that it has usually taken one generation 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.

11. FUTURE PLANS

The fuel cell bus tests will be continued in several European countries throughout the year 2006 under the title "Hy-Fleet:CUTE". In Iceland the focus will be on comparing several modes of running the production mode. Several patterns will be tested for the operation of the hydrogen production. The hydrogen buses will be driven during weekends and double shifts for example to try to make the hydrogen production more continuous and thereby cutting the running costs / unit of hydrogen. Within this project the performance of MAN buses equipped with internal combustion engines will also be studied. The final goal is to speed up the birth of a new and thoroughly tested hydrogen bus generation with all the benefits that these clean transport vehicles have to offer.

In Iceland, steps are also being undertaken to test stationary fuel cells for backup security systems and hydrogen equipment on board fishing vessels. The sea still provides for the highest national income and the exhausts from marine traffic are very high. Given the success and how far the fuel cell and hydrogen technology has come in 2005, the goal of total hydrogenisation of the Icelandic economy is not just a vision, but also a reachable goal – as long as other communities also press for further advancements and raise the overall demand for hydrogen technology.

No doubt that Icelandic New Energy has learned a lot from the implementation of the ECTOS, but DaimlerChrysler, Evo Bus, Norsk Hydro will be the ones that show how the learning will be integrated in technical terms within their future products.

12. CONTACT INFORMATION AND RELATED REFERENCES

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	Shell Hydrogen	www.shell.com
Related Websites	Clean Urban Transport for Europe	www.fuel-cell-bus-club.org
	Fuel Cells	www.ballard.com
	National Energy Authority	www.os.is