ECN
Energy research Centre of the Netherlands

HydroGEM, a hydrogen fuelled utility vehicle

Case Study

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Acknowledgement/Preface

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Abstract

This report describes the conversion of a Global Electric Motorcars (GEM, a Chrysler company) electric utility vehicle into a Fuel Cell Vehicle called HydroGEM, at the Energy research Centre of the Netherlands (ECN). The report is prepared as a case study within the framework of Task 18 on “Evaluation of Integrated Hydrogen Systems,” of the IEA Hydrogen Implementing Agreement. The vehicle’s fuel cell system was designed in 2005, manufactured and built into the vehicle in 2006 and operated from 2007 onwards. The design-choices, assembly, operation and maintenance-issues are presented and discussed.

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Project Date:	2005 - 2008
Case Study Date:	2009
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1. Project scope and goals

The HydroGEM project was about converting an existing battery electric vehicle (BEV) into a plug-in hybrid vehicle with a fuel cell range extender, using ECN in-house fuel cell technology and fuel cell system knowledge. After conversion, the vehicle was operated on the premises of ECN and displayed on many national and international occasions. There were several ambitions driving the project:

- ECN had been active in fuel cell R&D since 1990 and there was a need to demonstrate the application of in-house developed fuel cells in real world applications to create exposure for otherwise less visible activities;
- The application of ECN fuel cells in a real world demonstration vehicle would provide useful information on the operation of fuel cells under real world conditions outside of the labs;
- The HydroGEM could support the market introduction of ECN’s fuel cell stacks and fuel cell technology in general.

1.1 Project dates and duration

Project starting date:	January 2005
Kick-off:	March 2005
Project delivery date:	October 2006

1.2 Location

The HydroGEM is developed and operated on the ECN premises in Petten, The Netherlands. The premises are in general flat with a few bumps (dunes), windy and wet, conditions which influence the power demand as well the physical properties of the air being taken in by the fuel cell.

1.3 Participants and partners

The HydroGEM-project was an internal project of ECN. The System Engineering Group of ECN's Fuel Cell Department designed the fuel cell system for the HydroGEM. This system is based on a fuel cell stack developed by the PEMFC Research Group. The fuel cell system was built and tested by ECN's Engineering & Services department. Air Products provided a hydrogen refuelling unit.

1.4 Project size and funding sources

Initially, in 2005, a budget of 320,000- euro was established which was used to purchase and manufacture all the individual parts needed to build the HydroGEM and to pay for the labour required to build the vehicle and parts. The budget for the refuelling station has also been agreed on in this phase. In 2006, another extra 50.000,- euro was budgeted on the account of the HydroGEM vehicle. In 2007, an amount of 153,000- euro was made available for the HydroGEM demonstration project. In 2008, about 35,000 euro was made available to build a cooling-installation on the back of the vehicle to increase the usability of the vehicle. In total, 558.000,- euro (or 523.000,- without the cooling unit) has been spent on the HydroGEM project between 2005 and 2008.

1.5 Background and history

Fuel cell research at ECN started in 1985 with Molten Carbonate Fuel Cells (MCFC) for stationary applications. In 1991 Solid Oxide Fuel Cell (SOFC) development started for stationary applications. In 1995 Proton Exchange Membrane Fuel Cell (PEMFC) development started, the technology envisaged for transport applications.

The PEM fuel cell R&D is concentrated on material development, stack development and system development. For the development of the complete fuel cell system and its components it is necessary to design and build complete systems and test these systems in real life situations. The hydroGEM project intended to serve this purpose.

There are similarities with the EU-FRESCO[1] project, in which the same type of PEMFC stack is used for a 5 kWe HFC system for propelling a Piaggio scooter. There are also similarities with a project in which a basic design package was was developed to equip a three-wheeler battery EV with a PEMFC system; the FC-SAM[2] project. However, the conversion of the SAM, from the Swiss company Cree Ltd, was never realised at ECN.

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[1] http://www.onderzoekinformatie.nl/nl/oi/nod/onderzoek/OND1309339/

[2] http://www.onderzoekinformatie.nl/en/oi/nod/onderzoek/OND1309335/

2. Description of components

2.1 Short Description of components

The HydroGEM's point of departure is formed by a commercially available Long Utility Electric Vehicle (EV) from the OEM Global Electric Motorcars (GEM). The technical specifications of this EV are given in table 1.

Table 1: GEM long utility EV general specifications

Spec	Value
Curb weight	569.26 [kg]
Gross Vehicle Weight (GVW)	1043.26 [kg]
Payload Capacity	474 [kg]
Length	366 [cm]
Height	178 [cm]
Width	140 [cm]
Wheelbase	290 [cm]
Volume of Cab	1.33 [cub. m]
Turning Radius	5,33 [m]
Tires	12-inch
Range	48.3 [km]
Top Speed (High Mode)	40 [km/h]
Top Speed (Low Mode)	24 [km/h]
Baseload power	3.73 [kW]
Peak power	8,85 [kW]
Batteries	6 x 12V flooded electrolyte
Charger	On-board 72V DC charger, charging from standard 230V/7A AC outlet

The GEM EV is converted into a FCV, using the components (including the BEV) listed in table 2. The conversation of the original GEM BEV to a FCV does not result in modification of the existing drive line (electric motor, controller, battery pack).

Some of the components for the HydroGEM have been designed and manufactured by ECN, e.g. the DC/DC converter between the fuel cell and the battery as such device which appeared was not commercially available within the range of specs as desired for the HydroGEM[3]. Other parts could be purchased. The costs for the system design, assembly, testing and project management are excluded from table 2.

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[3] The DC/DC converter matches the PEMFC stack voltage, varying between 18 and 30 Volt, to the voltage of the batteries, varying between 72 and 80 Volt. The DC/DC converter is air cooled and has a conversion efficiency of 96%.

Table 2: list of components used to build the HydroGEM

Item	Supplier	Type	Capacity	Cost
Vehicle	GMS	GEM long Utility	40 km/hr	€ 11,850
H2 storage	Dynatek	W76, 200 bar	76 litre	€ 4,027
H2 storage aux	several			€ 647
PEMFC Stack	ECN	water cooled	5.4 kWe	€ 50,250
H_2 recirculation blower	H2systems Inc	HRB-L		€ 7,607
H_2 circuit aux	several			€ 1,271
Air blower	Vairex	VR-812	8 g/sec	€ 1,610
Air humidifier	Permapure	FC300		€ 1,698
Air circuit aux	several			€ 293
H_2 sensors	MST Technology	75-036203451009		€ 1,458
Cooling circuit	several		20 lpm	€ 898
DC/DC converter	ECN		5 kW	€ 9,100
Micro autobox	dSPACE			€ 18,022
Electric aux	several			€ 1,455
Support frame	ECN			€ 9,130
Total				€ 119,316

2.2 Selection criteria for the components

Within the window of boundary-conditions as marked by the GEM's layout, components were chosen on the basis of availability as well as their potential to contribute to a simple assembly of a robust, functional and fully operational FCV. As one of the consequences, the system is designed to be fuelled with hydrogen at 200 bar. The on-board storage tank is a TÜV certified Dynetek storage cylinder (200 bar, 76 litres, 32 kg gross weight, 1.3 kg H_2). The 200 bar gas-pressure was chosen to be able to fuel directly from 200 bar gas cylinders without the use of a compressor, and to avoid additional licensing-procedures for road-transport of hydrogen at pressures higher than 200 bar.

The power of the fuel cell stack was dimensioned on the basis of test-driving the original GEM electric vehicle around on the ECN premises and measuring the power demands of the electromotor. The average measured power-demand of the motor was the main argument to dimension the net power-output of the fuel cell stack at about 3.0 kW.

3. Integration of Components

3.1 Simulation and design

Starting point for the design was that the HydroGEM should be a simple, robust, reliable and functional vehicle. One of the ideas was that by minimizing complexity and reduction of parts, more reliability could be achieved.

The boundary conditions such as imposed by the operational conditions on the ECN premises were used as pragmatic input for the design of the system's power-specs. The electrical characteristics of the battery operated GEM vehicle were determined by means of test drives. Typical results from test driving at ECN are shown in figures 1 and 2. From the analysis of these data the nominal power of the fuel cell system was chosen as 2.6 kWe, with a maximum power of 5.4 kWe.

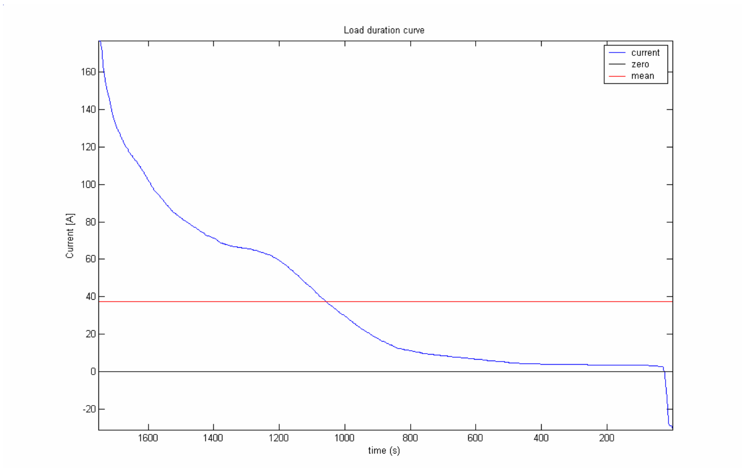

Figure 1: Load duration curve of the motor current during the testdrive with 300 kg payload. Average current: 37.3 A

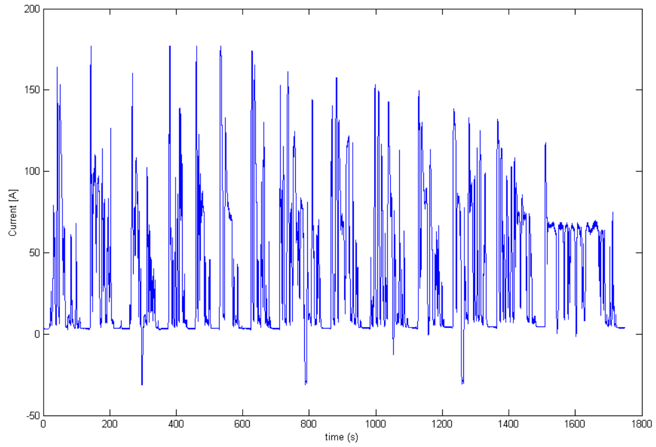

Figure 2: Dynamic driving pattern during an ECN test drive with 300 kg payload. Max. current is 180 A. The negative peaks are regenerative currents that occur during breaking.

The PEMFC fuel cell is used primarily to charge the batteries and is controlled by the voltage level of the batteries. The voltage output level of the batteries is kept between 72V and 80V to optimize battery life and vehicle performance. The batteries provide power during acceleration and they capture the braking energy during deceleration. The technology for regenerative breaking was already onboard in the GEM vehicle and thus was not modified. The vehicle is equipped with extra sensors and a “flight recorder” for monitoring and evaluation purposes.

In the design stage the system has been modeled using ASPEN+ software. Model simulations have been performed using the OEM specs of the different components, to yield the system design-specifications which are the reference values for later performance checks.

3.2 Process schematic

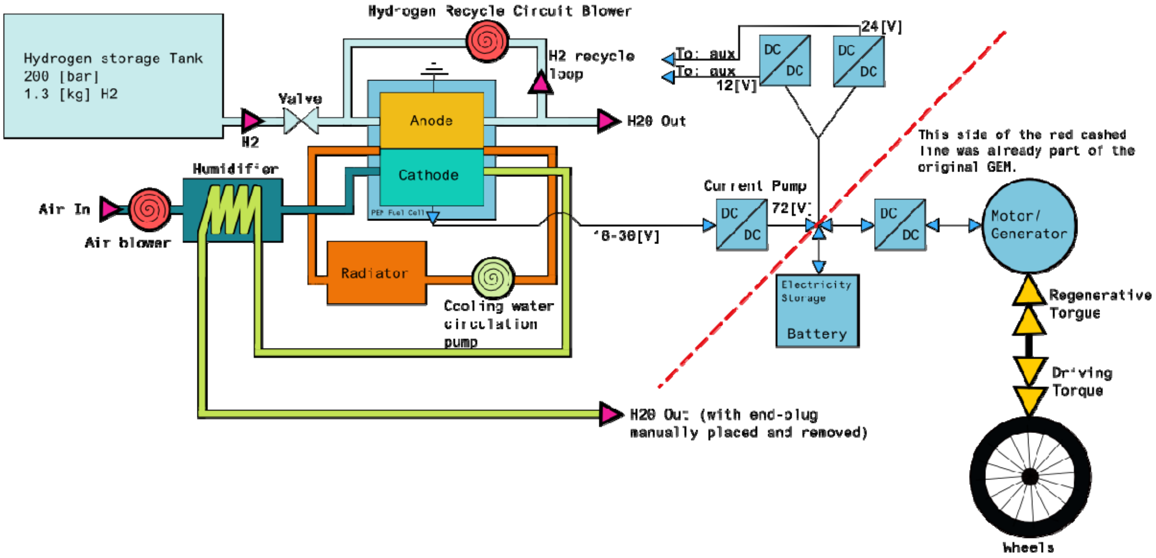

Figure 3: Simplified process scheme of the fuel cell system of HydroGEM. (Based on: *P. van den Oosterkamp, F. De Bruijn, R. Mallant, P. vander Laag, “Development and field trial results of a Hydrogen Fuel Cell Vehicle”, Fuel Cell Seminar & Exposition, San Antonio, Texas USA, Oct. 2007*)

A simplified process scheme of the fuel cell system is provided in Figure 3. In the figure, a schematic distinction is made between what is typical ECN’s own technological development, and what was already available within the GEM vehicle. A final overview-picture of the system assembly is shown in Figure 4. The hydrogen-tank is located behind the rear wheels.

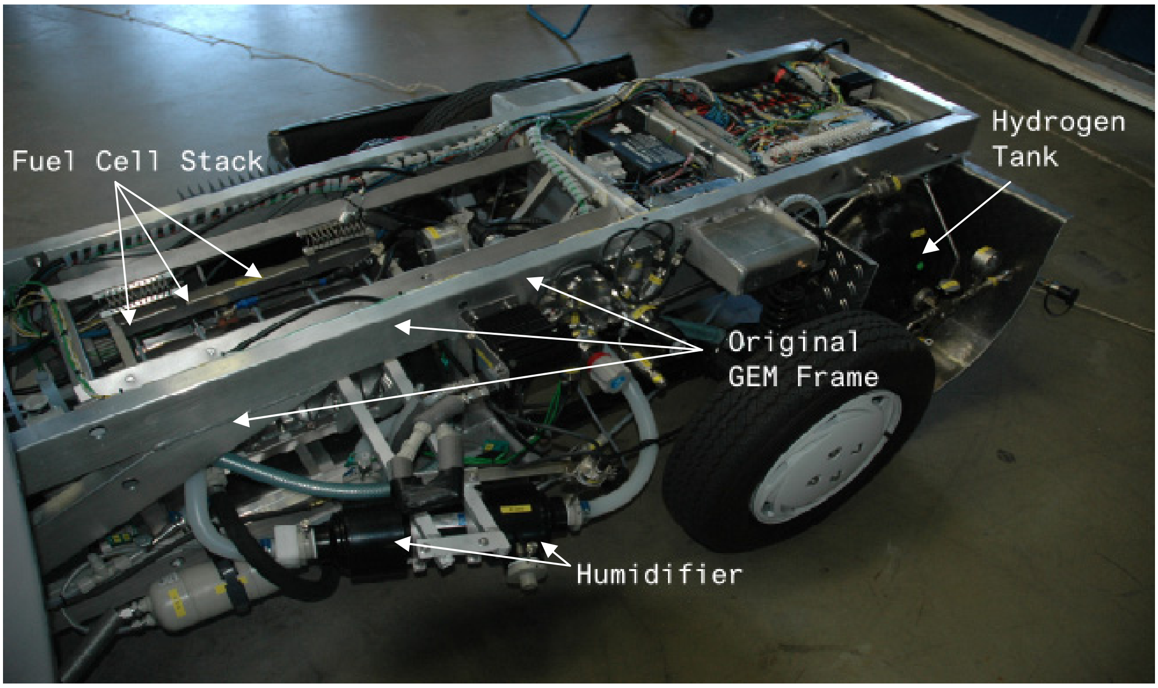

Figure 4: HydroGEM's fuel cell system with hydrogen tank

The HydroGEM vehicle was first configured with an open load space (left). Afterwards it was equipped with a cooling unit to be able to use the vehicle for catering purposes. The energy required for cooling is supplied by the batteries and thus integrated in the electrical system of the HydroGEM. The HydroGEM with the cooling unit built on top of its frame is shown on the right in figure 5.

Figure 5: The HydroGEM FCV before(left) and after installation of the cooling unit (right)

3.3 Control and data logging

The control of the drive train system is completely automated and is performed by a Micro-Autobox (MABX) controller which aslo serves as onboard flight recorder to record the process data during operation. One of the functions of the MABX is to control the operational parameters of the fuel cell. Therefore, The MABX monitors the setpoints of the inlet temperature, as well as the difference between the inlet- and outlet temperature of the fuel cell. With this information, the MABX can send a corrective signal to the circulation pump of the cooling circuit to adjust the flow-rate of the cooling-fluid, or to the fan on the radiator in the cooling circuit. Overall leading in the control of the system is the demand on the side of the current-pump (DC/DC – converter). All process parameters are optimized in function of this demand.

The MABX is also responsible for logging of the system data during operation. However, it turned out that the memory of the MABX only provided space for 1.5 hrs of data logging. In practice, this proved to be insufficient for proper monitoring purposes. Failure mechanisms often occur over time-spans longer than 1.5 hours. The information saved in a 1.5 hour buffer will in many cases only log the final event in a sequence of events which led to failure or performance change, but will miss the events which actually triggered the last event.

From a monitoring and evaluation perspective, it becomes apparent that insufficient pro-active emphasis has been put on monitoring and system evaluation during the design phase of the project. Despite that learning from experience with the fuel cells in real world conditions was one of the ambitions, the realisation of this ambition has not been looked after seriously enough during the whole project.

3.4 Start-up and shut down procedure

When the fuel cell system initiates its operation, a start-up procedure will start in which the cathode side of the fuel cell stack is flushed with air. When operational, the hydrogen flow is recirculated through the PEMFC stack and regularly purged to remove excess water and possible contaminations. During driving, the fuel cell system is operated to keep the output voltage of the batteries within the required window of 72V-80V. After parking the vehicle, the FCS continues to charge the batteries until the required voltage is reached; then the fuel cell is shut down. At that point, water at the cathode side is removed by a flush with air and the anode is purged with hydrogen. In case of failure in the system or hydrogen detection in the cabin, near the stack or near the hydrogen pipelines, the main valve on the hydrogen tank is closed automatically and the fuel cell system is stopped. Furthermore, a lit is manually put on the exhaust-pipe after operation, to keep moist in the system to prevent the fuel cell to dry out during idle-time.

4. Performance and operational experience

4.1 Efficiencies

Energy efficiencies are calculated to ensure that system expectations, based on the initial computer simulations, are met, or not deviated from too much. In case of large deviations, this may potentially also indicate errors in the system or system-design. Furthermore, the efficiencies are relevant in the context of one of the primary goals of the application of fuel cell systems: the reduction of energy consumption and of emission of greenhouse gases. In case the HydroGEM is fuelled with hydrogen produced by steam-reforming natural gas, then kilometres driven per kilogram hydrogen, translates indirect to a value of the indicator "CO2-equivalent per kilometre".

The efficiency of the ECN current-pump (or DC/DC converter) which converts the DC power from the stack at 20 V to a DC power at 72 V required by the battery and the electromotor, is calculated from loggings of the vehicle in operation as 96% (design value 95%). The 4% losses in the current pump, result in a loss of 1.5% relative to the total system. The energy balance for the HydroGEM system is shown in Figure 6. The part "Other losses" contains those losses, which cannot directly be assigned to obvious system components, but rather to operational necessities such as flushing the system with hydrogen which is lost. The resulting system efficiency is calculated as 29,6% (Energy to electromotor/ Energy(LHV) of the hydrogen consumed) for the period considered. Start-up and shut-down effects on efficiency are not accounted for.

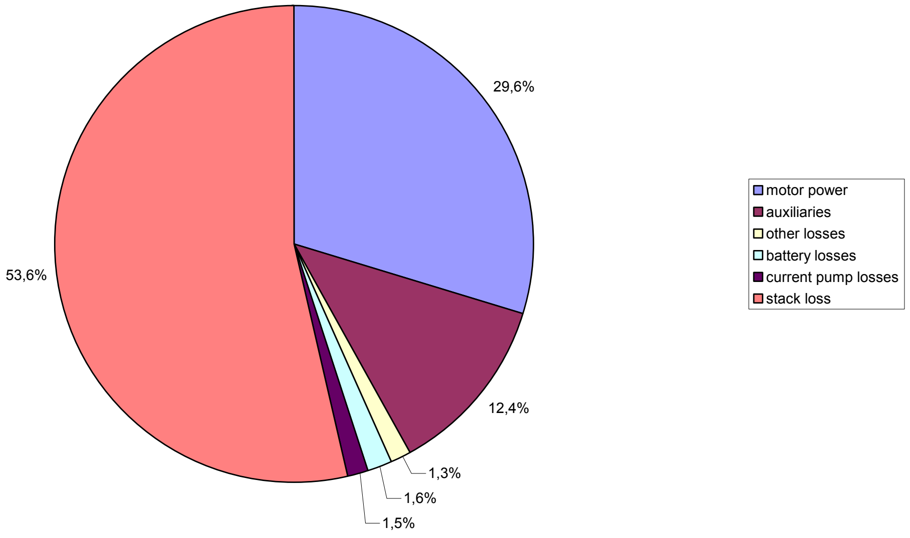

Figure 6: the complete energy balance of the HydroGEM

4.2 Energy use

The fuel consumption of the HydroGEM is estimated from a dedicated test driving sequence as 160 km/kg H2. The driving range on a full hydrogen tank is approximately 175 km. On full batteries the vehicle could maximally drive 56 km, so the cumulative of the two is close to the 200 km that was anticipated on the hydrogen alone. In other words, the fuel cell extends the range of the vehicle if it would only contain a battery, with a factor 4.

4.3 Number of running hours, operation hours

In 2007 the vehicle has driven 305 km, around 40 km only on the batteries and 265 km using also the fuel cell system. Assuming an average speed of 20 km/hr this leads to approximately 13 operating hours for the fuel cell system. The hydrogen tank has been refilled four times. The total hydrogen refill in 2007 was 2.0 kg of H2.
The same concern can be expressed here as is mentioned in the context of the logging capacity of the MBAX control unit. The limited amount of kilometres driven, has reduced the insight into the vehicle's road-worthiness. Typical parameters such as Main Time Between Failure (MTBF) as well as total mileage before replacement, are important in order to be able to compare fuel cell technology with conventional vehicles. Conventional diesel vehicles typically drive 200.000[km] before they are fully depreciated by the operator. Although it cannot be expected from a new technology to stand the competition of conventional, fully developed technologies, durability logging is a typical example of a logging which matters when thinking of commercialization of fuel cell drive train technology.

4.4 Load factors

In a special test drive at the end of 2007, the fuel cell system operated at a power level of 1 to 2 kW, where 3 kW was expected from the IV curve of the stack. Subsequent tests revealed that the recirculation blower overheated and the recirculation rate was low. Also condensation of water damp in the air and hydrogen piping was observed.

After the replacement of the recirculation blower and an improvement of the thermal insulation of hydrogen recirculation pipeline-circuit, another test drive was performed on 30.05.08. The maximum output of the system measured after the current pump was 2900 W, see figure 7; the mean power output was about 2kW.

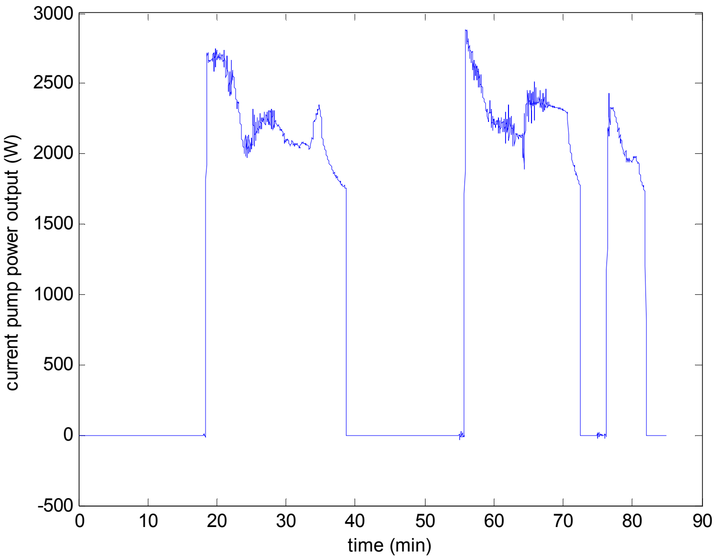

Figure 7: Power measured after the current pump

For evaluation of the energy balance of the HydroGEM system, the energy-flows to different parts of the system are measured under the condition that the state of charge of the batteries is identical at the start and end of the evaluation period in the second run, i.e the period between 39 and 79 minutes. In this period, the battery capacity varied within 2% of the total capacity of 90 Ah with an efficiency of 93% (=Energy from battery/Energy to battery). The current flows in the system are shown in figure 8. The current from the current pump, to and from the batteries, to and from the motor and to the auxiliaries are shown. The current to the auxiliaries follows to a large extent the current from the current pump.

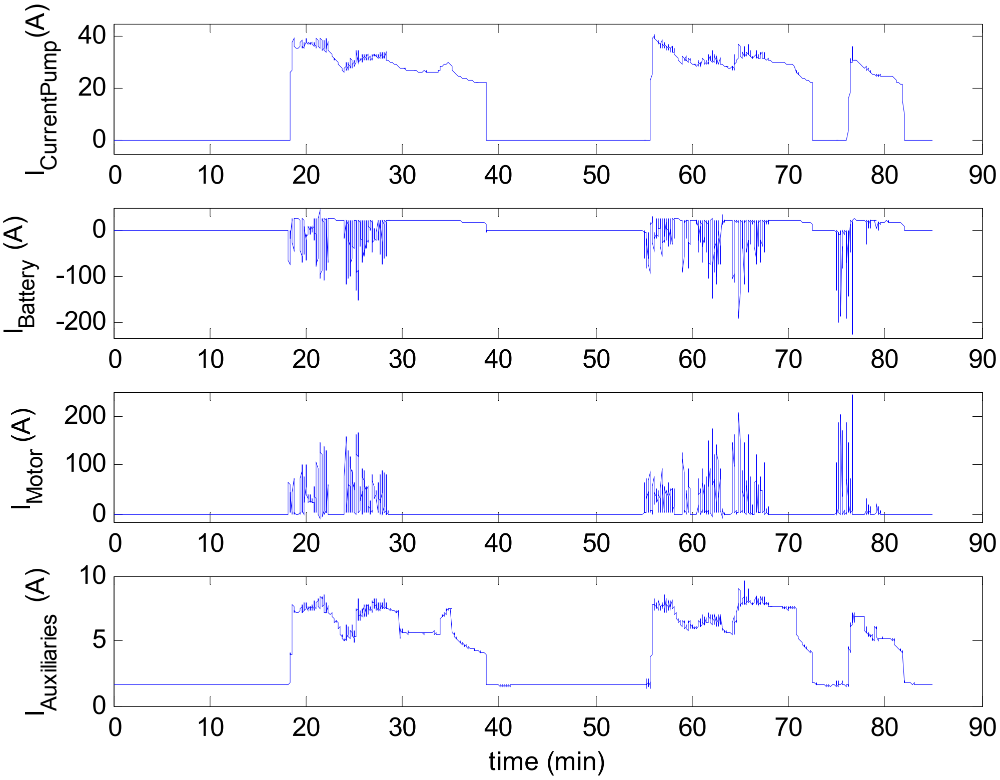

Figure 8: Current flow in the HydroGEM fuel cell system from the 72 V busbar

4.5 Failures and availability

Operational characteristics for the test period are listed in table 3.

Table 3: Failures encountered during the test-period

No	Problem	Cause	Repair/solution
1	Battery failure	2 Month idleness and thereby deep discharging of the batteries	Replace battery pack Regular charging of battery pack
2	H_2 leakage of 1% of the H_2 flow	Leakage of the seal surrounding the H_2 in 2 cells	Replace 2 cells in the stack
3	Battery capacity degradation		Smart loading/unloading cycles for the separate batteries
4	Current pump failure	Bolt has gone loose and fell on the current pump causing a short-circuit. Potentially caused by the stone pavement on the premises.	Repair current pump
5	Current pump failure	Human error caused short-circuit	Repair current pump
6	FC stack powerloss	Degrading of the stack	Suppressing the stack voltage by squeezing the dc/dc converter.
7	Dry FC stack	Operation in unconditioned mode.	Modification of the cooling system.
8	Low stack Output	Failure of the H2 recirculation blower, most likely due to poor performance of bearings.	Replace blower.
9	Hydrogen recycle blower shut down	Moist on the Hall sensor in the blower.	Change position of the blower (moist will now run down). Change controls: blower will blow at full power shortly after shutting down the Fuel Cell, so it dries itself. Insulation of the recirculation piping.

4.6 Theory vs. practice

Initial measurements of the system appeared to be insufficient for system-performance mapping. Additional measurement of currents in different parts of the system was necessary to be able to determine the efficiency of charging/discharging of the batteries, the current pump and the auxiliaries.

Furthermore, practice proved the relevance of measuring the temperature in the hydrogen storage tank. This temperature measurement allows for improved calculation of the hydrogen content of the tank. As a result, fuel-consumption (kg/km) and hydrogen losses can be quantified more precisely.

The algorithm controlling the temperature of the fuel cell also proved in practice to have its weaknesses. The algorithm is based on the setpoints “temperature inlet” and “temperature difference inlet / outlet”. The effect is that the control follows on temperature on the inlet, but the system does not pro-actively influence the inlet temperature during extreme cold for example. During windy, cold days, the fuel cell had trouble getting on its optimal operational temperature. This was caused by the cold winds blowing over the cooling-circuit's pipelines and auxiliaries, decreasing the temperature of the cooling-fluid more than desired.

Because the cooling-circuit has 2 parameters that can be controlled, flow-rate of the cooling-fluid and airflow-rate of the radiator's fan, it also happened that the temperature-gradient over the stack got too big. This happened when the flow-rate of the cooling-fluid was too low and the airflow-rate of the radiator's fan too high.

Also overheating of the fuel cell occurred. This happened most likely when the fluid-pump of the cooling circuit failed or when the control-system of the fluid-pump and the radiator's fan reacted with delay.

Improvements have been introduced in the control-strategy of the cooling-circuit. The fluid's flow-rate is used to minimize temperature-difference over the stack while the fan is used to control the maximum temperature. Desired hardware changes, such as a bypass to circumvent the radiator, have not been applied due to budget limitations.

4.7 Maintenance

During use in practice, it became more obvious that the HydroGEM was not built with maintenance in mind. Low visibility of essential water levels in the water-reservoirs for example has lead to unnecessary drying out of the FC. Furthermore, it appeared that fitting and removing components sometimes led to long overhaul times because of the inaccessibility of parts. Also, the availability of spare parts was not foreseen in advance and therefore not organized. It should be noticed however, that many parts were also relative novelties for the manufacturers who provided them, hence had not fully overcome teething problems yet.

These issues were not really high on the priority list of the HydroGEM project which is understandable when looking at the initial ambitions that drove the whole project at the first place. In follow-up projects, however, it is necessary to pay much more attention to this issue as maintenance and repair requirements as experienced with the HydroGEM vehicle will not be acceptable for (semi-)commercial systems.

5. Environmental aspects and safety issues

The design of the fuel cell system follows the standard NEN 3140 for electrical devices and standard PED for the pressure devices. The design was checked for safety aspects by an internal HAZOP study.

The filling station was delivered by Air Products and shown in Figure 9. Concrete blocks protect the filing station from collisions. The HydroGEM vehicle is shut down and grounded before connecting the flexible hydrogen filling hose to the vehicle for eliminating static discharge that could ignite accidentally released hydrogen.

Figure 9: Photo of the 200 bar hydrogen filling station delivered by Air Products

6. Permitting and Safety

It was decided that the vehicle would not be licensed for public road transport outside the premises of ECN. The reason for this is the requirement of safety documents for the type approval of the vehicle by the Rijksdienst Wegvervoer (RDW) that are costly and the vehicle is mainly for internal utility purposes. The consequence is that a driving demonstration outside the premises is only possible on other private or closed premises.

Since the HydroGEM vehicle is also a mobile testing station, approval from the local authorities, the Milieu Dienst Kop van Noord-Holland, was needed and granted. For this they need a technical information package. For access to the part of the premises with nuclear activities, additional safety calculations like a maximum credible accident had to be made.

7. Education, Training and other experiences/issues

The drivers that were asked to drive with HydroGEM were trained for about 1 hour, including a test drive. The main items to be taught were safety, how to drive the vehicle (start-up, operate, shut down), and what to do in case of anomalies.

8. Economic considerations and cost

Apart from the investment in hardware as described in chapter 5, also the design, the control system and the assembly of the components required an investment in personnel of 330 k€. The costs for operation and maintenance of the vehicle are included in the project costs for the market development of the HydroGEM vehicle.

The benefit of investment in the HydroGEM vehicle is that it is a showcase of the competences as well as the determination of ECN in the field of fuel cell systems. The vehicle has been displayed on the AutoRai car fair. The vehicle attained great interest from policy makers (e.g. minister van der Hoeven), press (e.g. BBC) and industries.

9. Future plans

ECN has started a small spin-off company E-sys2Go. All knowledge and experience of the HydroGEM project and earlier projects in the field of design, assembly and operation of fuel cell systems is brought together in this company. The company focusses on providing services or developing tailor made fuel cell system solutions for customers looking for support in entering the growing market of fuel cell niche applications.

10. Conclusions and recommendations

The different ECN departments that worked together on the HydroGEM vehicle have managed to design and assemble a fully functional fuel cell vehicle. Operation of the vehicle is experienced as relatively simple, though special instructions have been provided to the drivers of the vehicle for safety reasons, which is not unusual given the experimental aspects of the project.

When trying to generally describe the state-of-technology as applied in the HydroGEM in terms of durability and reliability, the experience teaches that more sophisticated control solutions and algorithms are required to maintain the fuel cell stack operation on a reliable and durable level. Despite the initial idea that the reduction of complexity would contribute to reliability and durability, the sensitivity of the fuel cells requires more complex systems.

The HydroGEM project has been successfully achieving on of its other initial ambitions to create more exposure for ECN's own fuel cell development program. The HydroGEM has had a lot of media attention due to test-drives by for example different national ministers. Although it is difficult to exactly quantify the net result, there is reason to believe that the HydroGEM has lead to increased business activity in the field of fuel cell technology.

Despite that the vehicle had the potential to be a perfect platform for testing ECN's fuel cell stack under real world conditions, this potential could and should certainly have been exploited better. A limited budget, but also limited consideration paid to system testing and monitoring in the design phase, has lead to a limited amount of collected data which is insufficient to build robust conclusions on in terms of system performance in time. This should be taken into consideration in future conversions.

The overall energy efficiency of the vehicle (from tank to wheel) was determined to be 29.6%. The relatively low efficiency can certainly be explained by the energy consumption of the auxiliary systems, which required 12.4% of the total energy consumed by the vehicle. Fine-tuning and technological development could contribute to a reduction of energy consumption of the auxiliaries and deserves therefore future attention.

Because there was no DC/DC converter on the market that matched the specific requirements of the HydroGEM conversion, ECN has successfully developed its own DC/DC power-converter in-house. This "current-pump" proved very successful in its task and because of the unique value of this DC/DC power-converter in the market, it has created a commercial demand by third parties, like for example the Formula Zero Carting team.

Further information/contacts

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References

P. van den Oosterkamp, F. de Bruijn, R. Mallant, P. van der Laag, “Development and field trial results of a hydrogen fuel cell vehicle”, 2007 Fuel cell seminar, San Antonio, USA