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Department of the Environment, Transport, Energy and Communication DETEC

Swiss Federal Office of Energy SFOE
Hydrogen and Fuel Cell Programme

Final report

Integration of a 10 kW Fuel Cell in a Hybrid Range Extender Vehicle

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Summary

The project "Integration of a 10 kW Fuel Cell in a Hybrid Range Extender Vehicle" had as main objective the integration of the fuel cell developed in a CTI project (13999.2 PFIW-IW) in a road worthy vehicle. Once fully integrated, the entire fuel cell system was tested and validated under real driving conditions and in all seasons. The collection of usage data under these realistic usage conditions was an important aim. These data have allowed in depth analysis of the real life, on-the-road behaviour of all the components integrated on the fuel cell system, an important step in the direction of a commercial product.

The vehicle, a Fiat 500 converted to electric power by Ökozentrum in Langenbruck, has successfully been converted to a fuel cell hybrid. The mechanical and electrical integration has been performed taking into account the very limited space available and all the necessary security requirements. The vehicle has been tested with great satisfaction by several drivers of PostAuto in Brugg.

The collection of usage data under real life conditions has been implemented and running without interruption from the first kilometres that the vehicle has run. The vehicle has been running for over 90,000 km during the course of the project. This comprehensive collection of log data has given us a valuable trove of information for debugging, understanding and optimizing the system. At present the log files make about 43 gigabytes of information.

In the course of this reliability testing several unexpected problems have presented themselves. These have been resolved or are now in resolution. Reliability testing is still continuing after more than 100,000 km.

Contents

1. Fuel cell system

1.1 Fuel cell stack

The fuel cell was developed in the frame of a CTI project (13999.2 PFIW-IW), which aims to develop a 10 kW H2-air fuel cell (FC) stack for automotive applications based on innovative Swiss technology for air compressors. The goal is to provide a FC system using air as oxidant offering a) an excellent fuel efficiency and b) compactness and price-worthiness close to the performance achieved with a pure oxygen FC system.

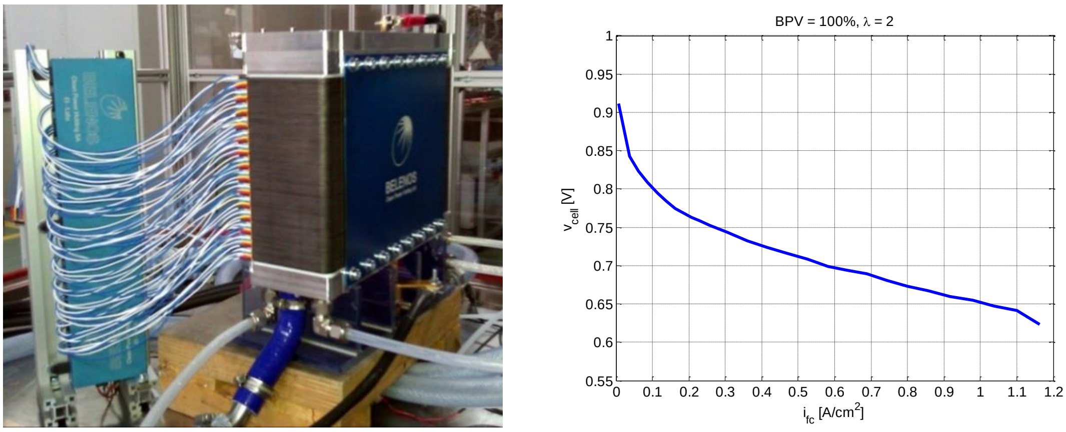


Fig. 1: The 10 kW fuel cell stack developed in the frame of a CTI project (13999.2 PFIW-IW) and its polarization curve.

As shown in Fig. 1, the fuel cell stack was able to produce up to 12 kW with 80 cells and a cell voltage of 0.65V at 1 A/cm^2. This achievement places the Swiss Hydrogen fuel cell among the best performance of reported fuel cell stacks usually achieved with close to 100 kW stacks (Fig. 2).

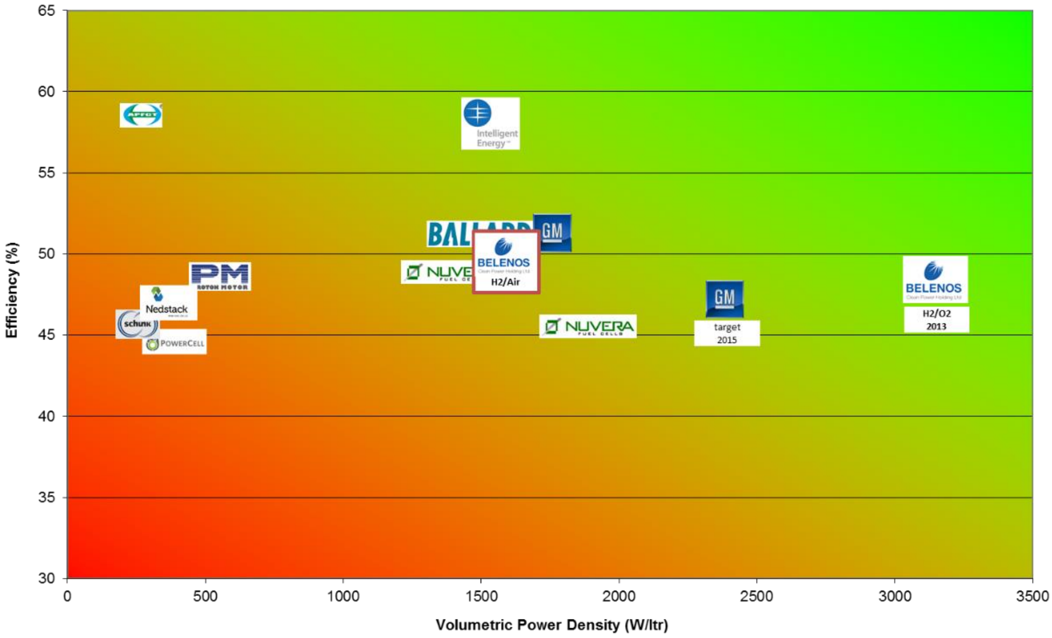
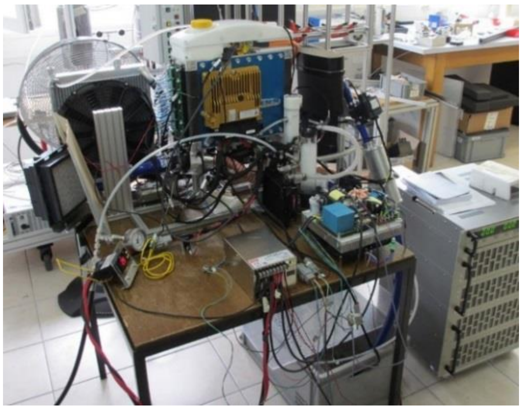


Fig. 2: The 10 kW fuel cell stack (tagged with the Belenos logo) among best reported performance.

1.2 The 10 kW fuel cell system

The 10 kW fuel cell complete system (Fig. 3) includes cell voltage monitoring (blue and white wires on the left) and the gold colored electronic control unit (ECU) which controls the system. At the top is a reservoir for the coolant liquid. Below the blue colored stack itself is the system endplate which includes the gas and air inlets and outlets as well as the cooling circuit connections.

We see on Fig. 3 the 10 kW fuel cell on a test bench simulating the environment in the vehicle. On this test bench all the components are placed in the same relative positions as they will be in the vehicle. This allowed making all the cabling and tubing/piping necessary before the installation in the vehicle on a table where access for working was much easier. Note the radiator and ventilator at the left, the black air humidifier at the right and the silver cylinder at the right which is the silencer for the air outlet.



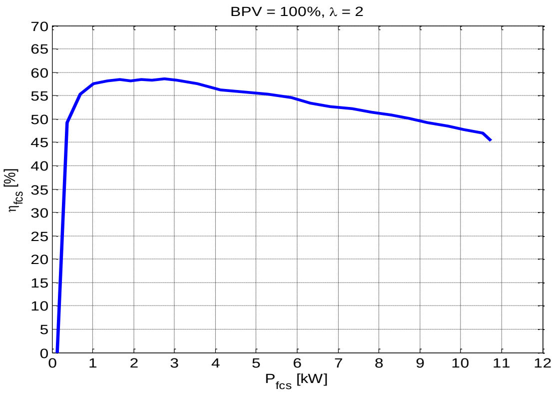


Fig. 3: The 10kW complete fuel cell system and its performance curve.

A system efficiency of 48% was achieved at a system power of 10 kW_{net}. The good performances achieved were possible with a newly developed compressor from the Swiss company Celeroton (www.celeroton.com). The compressor has a high rotational speed (280,000 rpm) which reduces its size and increases its efficiency. This compressor is able to provide an air flow of 10 g/s at 1.7 pressure ratio. The electrical consumption remains lower than 1 kW at full load, corresponding to 10% of the rated fuel cell power. This brings the overall fuel cell system efficiency to the best achieved ever (near 60% at partial load).

The hybrid ECU functions are carried out by the fuel cell ECU shown here as mounted on the fuel cell. This ECU is a standard unit made for controlling diesel engines. It includes all the I/O and processing power needed to control the fuel cell. The programming is done in MATLAB/Simulink using I/O libraries supplied by the ECU supplier.

For the integration into the vehicle, the fuel cell itself can hardly be seen, packaged as it is between the radiators and the DC/DC and junction boxes (Fig. 4).

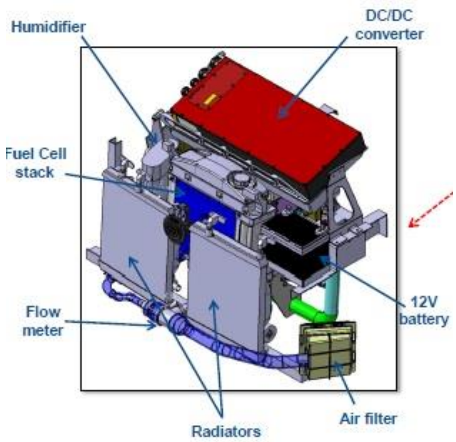


Fig. 4: The CAD of the complete fuel cell system as projected for its integration into the vehicle.

2. Mechanical integration cell system

2.1 Initial position

While the Fiat 500 (diesel) was converted into an electric vehicle by Ökozentrum in Langenbruck, we had to take a similar battery vehicle as a template for the integration of the fuel cell system. The Fiat 500 is known not to have too much room available and the fuel cell system, though only 10 kW, still required some volume (Fig. 5).

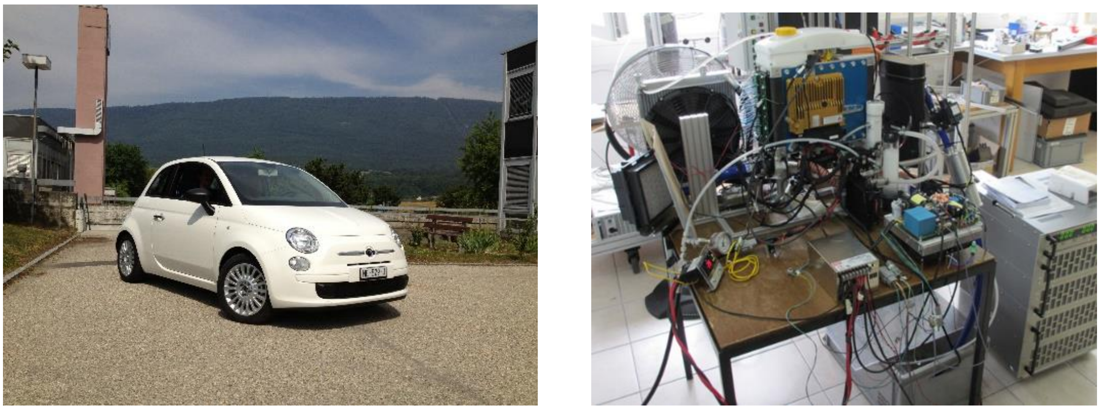


Fig. 5: The Fiat 500e and our 10 kW fuel cell system without the hydrogen tank.

2.2 3D-scan of the vehicle

The first major step to the integration of the fuel cell system in the Fiat 500e was to measure the space we have available for the fuel cell and its support system. To this end a 3D scan was made of the engine compartment and the rear of the vehicle. A similar vehicle was driven to Gempen, SO, where the 3D scan was made by the company Sauter Engineering+Design.

A 3D scan results in a point cloud defining the surfaces seen by the 3D camera. In our case much clean-up work was necessary using our 3D modelling software CATIA. This clean-up was mostly to remove components that could not be removed physically at the time of the scan.

The type of images produced can be seen in the images below.

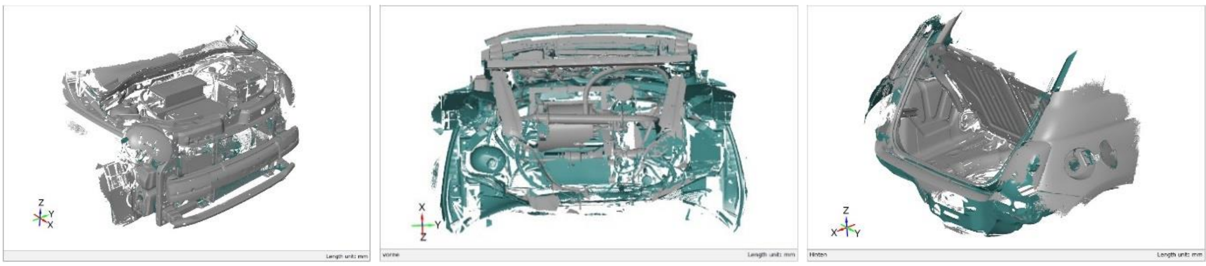


Fig. 6: 3D scan results of the Fiat 500e, front from above, front from below and rear.

Because of the high computational demands of such a high resolution point cloud a simplified version was made using the info from the scan. This was used to prove the technical feasibility of the installation and define the mounting points for the brackets for all the system parts.

Some difficulty was caused by shading of the engine compartment surfaces by components that were later removed. Because of these components the 3D camera couldn't always see the surfaces that were interesting for us. These surfaces then needed to be added in our 3D model. The shaded areas caused significant supplementary work that we had not expected. However, with 3D modelling

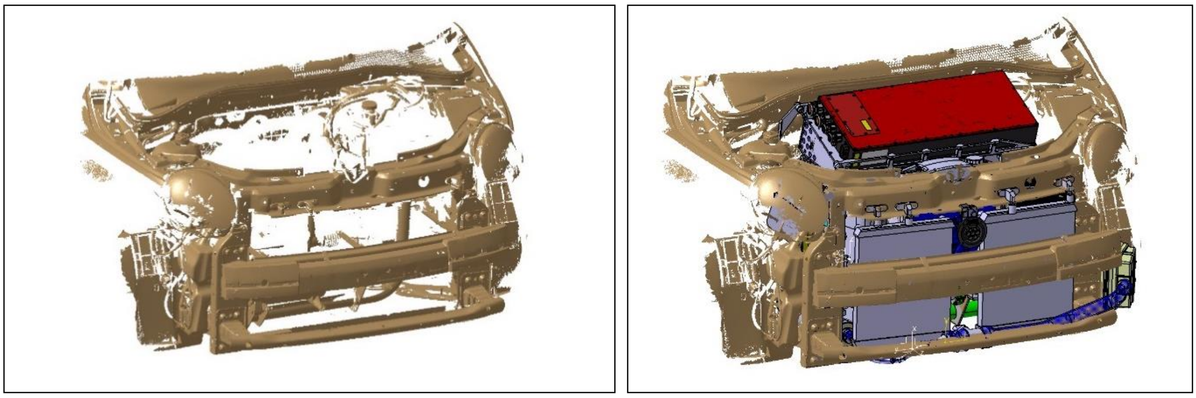


Fig. 7: Simplified scan of the Fiat 500e and simplified scan with integrated fuel cell system.

software we were able to virtually place the entire fuel cell system with its support systems like the compressor and power electronics in the vehicle, as defined by the point scan.

As can be seen here it was then possible to measure between points to be able to verify the correctness of the 3D model. Finally, the 3D scan gave us essential information for the integration of the fuel cell system in the Fiat 500e vehicle. The amount of work necessary for cleaning up the point cloud was greater than we had anticipated, but at the end, the 3D scan information allowed us to have confidence that the integration would proceed without surprises.

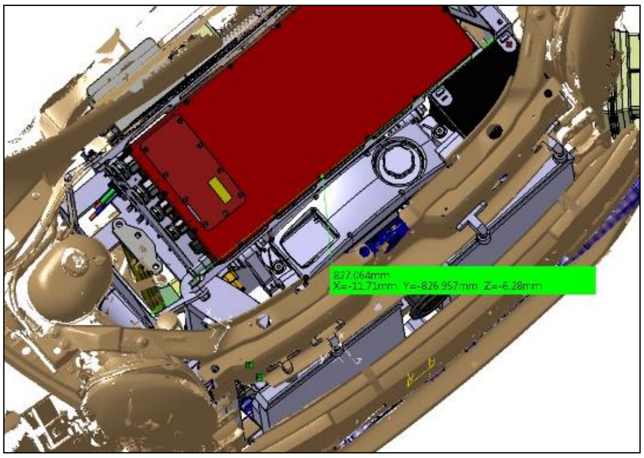


Fig. 8: Simplified scan with integrated fuel cell system and points measurement for 3D model verification.

2.3 Parts for mechanical integration

The mechanical integration of the fuel cell system in the Fiat 500 required nearly 80 parts to be made.

- Design of supports and fixtures
- Adaptation of parts to fit in the Fiat 500
- 3D Design of nearly 80 parts
- 2D detail drawings of all fabricated parts
- Machining/fabrication of all the parts
- Assembly drawings including exploded views.

2.4 Mechanical integration of the hydrogen tank

As the H2 tank is mounted in the passenger compartment it must be in a gas-tight housing. The housing is vented at the top with a tube that leads to the exterior of the vehicle. The housing must also be able to securely hold the H2 tank in the event of a crash. To keep the weight within reason it was decided to make a housing in carbon fibre. An FEA analysis was made with an external consultant to assure the integrity of the housing in the case of a crash.

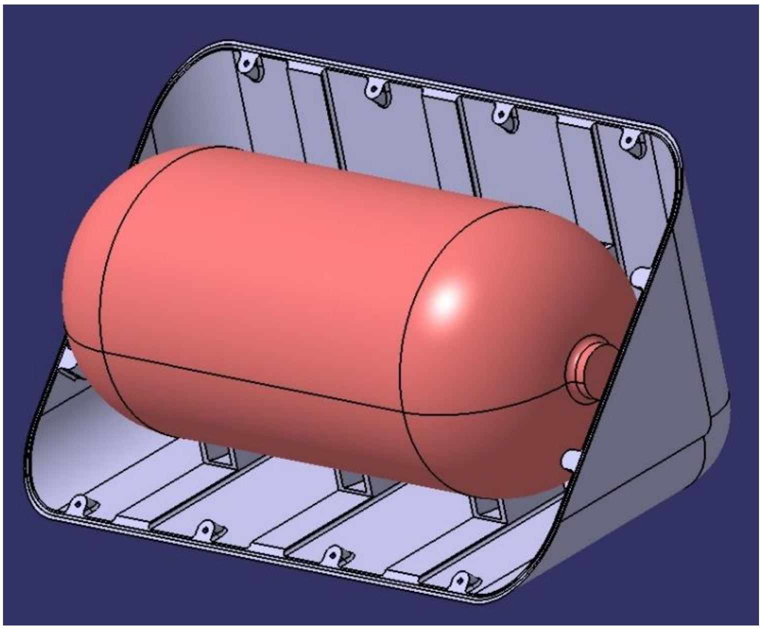
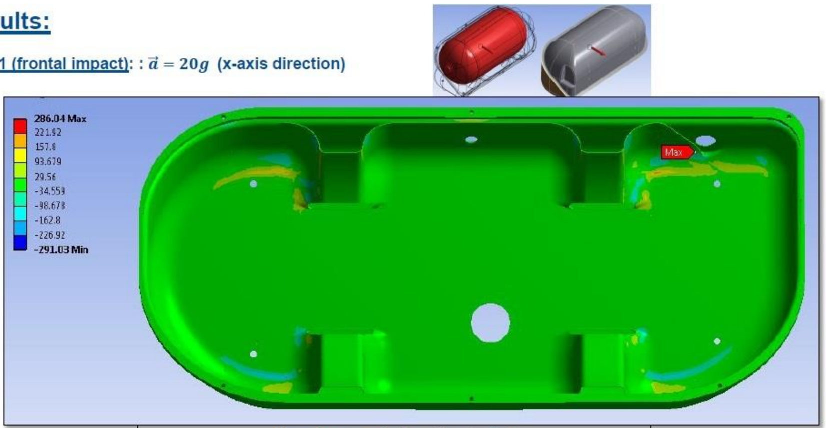


Fig. 9: CAD of half of the gas tight housing for the hydrogen tank.

Results:

Case 1 (frontal impact): : $\vec{a} = 20g$ (x-axis direction)



Normal stresses in the x direction (σ_x)

Calculated stresses →

		Stress (MPa)	Stress (MPa) Reinforced structure	First failure stress (MPa)	Safety factor	Safety factor (reinforced structure)
σ_x	tensile	286	134	733.487	2.5	5.4
	compressive	291	136	704.836	2.4	5.17

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Fig. 10: FEA calculation results showing the fixation of the hydrogen tank is strong enough in case of crash.

Fig. 11: Fixation system of the hydrogen tank.

Fig. 12: Carbon fibre gas tight housing covering the hydrogen tank and its connections.

3. Electrical integration

3.1 Initial situation

The Fiat 500 vehicle has had the combustion engine removed and replaced by a 21kW electric motor. A battery of 31kWh has been mounted below the vehicle. The electrical system is based on the power electronics supplied by MES in Stabio TI. The battery system is a development of the Ökozentrum in Langenbruck BL (Fig. 13). It is mounted below the vehicle and follows lower surface of the floor. The battery is passively cooled. As it is thin and flat it has a large surface and we have not seen any problems with cooling. For reasons of durability, the BMS of the battery limits the usable electric energy to 26kWh.

The inverter is a standard unit TIM600 supplied by MES in Stabio TI. The DC input voltage range is 80V to 450V. The peak current is 400A, nominal current 266A. The inverter is liquid cooled.

Fig. 13: The battery supplied by the Ökozentrum Langenbruck BL.

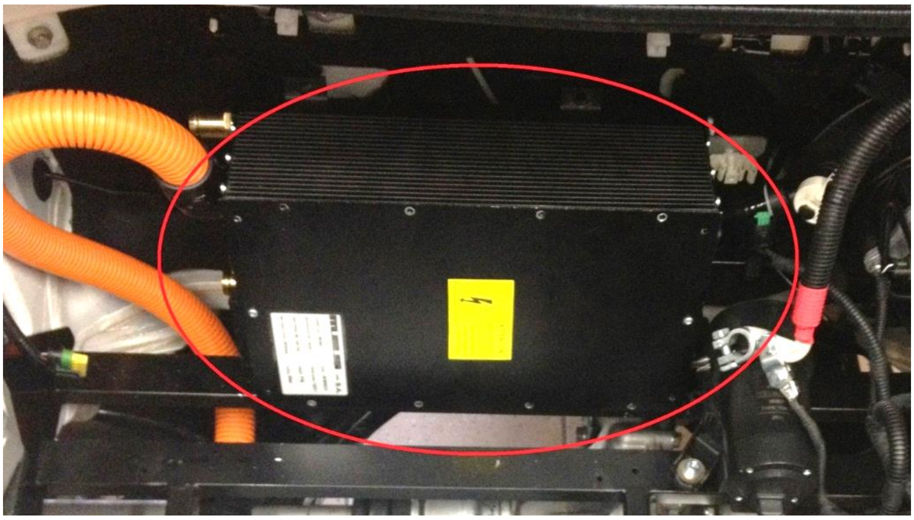


Fig. 14: The inverter TIM600 supplied by MES.

The traction motor and reducing transmission are also supplied by MES. The mounting bracket for the Fiat 500 was designed for this purpose. The unit has a nominal power of 21 kW and a maximum power of 60 kW. The motor is liquid cooled.

Fig. 15: The 21kW nominal power (60kW peak) electric motor supplied by MES.

Taking into account that the car will carry 1.7 kg of hydrogen (55 kWh chemical energy), the total on-board usable electric energy is the following:

	Mass	Power	Chemical Energy	Electrical Energy	Range (NEDC)	Filling Time
HV Battery	210 kg	60 kW	31kWh	26 kWh (124 Wh/kg)	200 km	10 h
FC system	125 kg	10 kW	55 kWh	26 kWh (208 Wh/kg)	200 km	2 min

Table 1: overview of the total on-board usable electric energy.

The range was estimated using New European Driving Cycle (NEDC) which usually gives very optimistic numbers. However, we will see that this range has been achieved on normal road conditions, using the “Eco Drive” mode.

The fuel cell system will serve as an on-board charger for the battery to support the battery while driving. As such the fuel cell system voltage must be adapted to the battery voltage of the pure electric vehicle. A user interface allowing starting and stopping the fuel cell as well as displaying driver-relevant information about the fuel cell system must be developed.

A high level block diagram of the electrical system of the Swiss Hydrogen Range-Extender fuel cell vehicle is shown below.

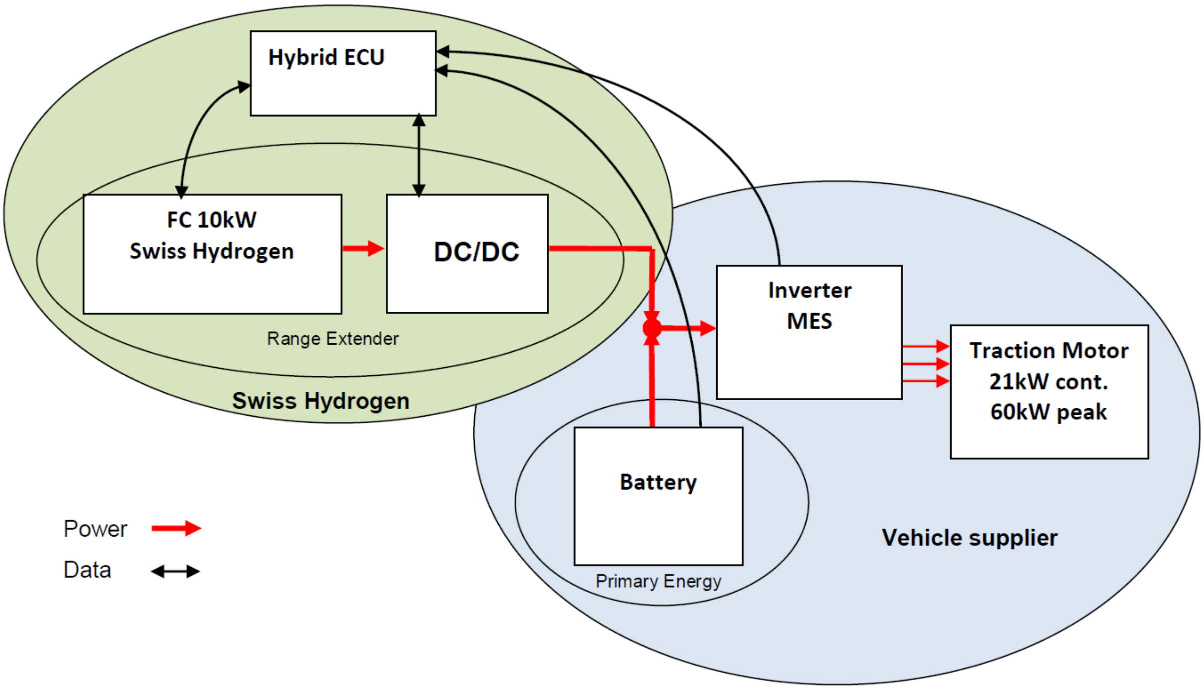


Fig. 16: Block diagram of the electrical system of the Swiss Hydrogen Range-Extender fuel cell vehicle.

FC 10 kW	The 10 kW Swiss Hydrogen fuel cell system is an autonomous system including a hydrogen tank which can store 1.7 kg of hydrogen. The system includes humidity management, cooling and a control computer ECU (electrical control unit) which automates the system.
Hybrid ECU	The Hybrid ECU (electrical control unit) is charged with controlling the high level energy management of the entire vehicle. It receives information from the traction inverter, the traction battery, the DC/DC converter and the fuel cell system to decide how the FC system should best be run to have the best fuel economy and vehicle dynamics. The implementation of optimised control strategies for the hybrid ECU is one of the goals of this project. In this vehicle the Hybrid ECU is implemented in the FC ECU. A further low level safety controller called the HSL (hardware safety layer) controls the supply of hydrogen without the use of a processor or any program code.
DC/DC	The traction DC/DC adapts the voltage level of the FC output to the voltage level of the traction battery. The DC/DC converter chosen is supplied by Brusa Electronik AG in Sennwald SG.
Battery	The 31kWh Lithium Ion battery pack is a development of the Ökozentrum Langenbruck BL. It is integrated as very flat package below the vehicle. This package form has a large exterior surface allowing passive conductive cooling. The voltage level is from 280 to 410 volts and the maximum discharge power 60 kW.
Inverter	The traction inverter is a standard unit from MES in Stabio TI and is well adapted to the voltage and power levels of the battery.
Traction Motor	The 21 kW continuous power (6 0kW peak power) traction motor is also supplied by MES as well as the speed reducing gearbox. It is designed for application in electric vehicles.

3.2 Voltage adaptation

The electrical integration principally involves adapting the voltage levels of the different components to each other. The electrical vehicle without the fuel cell runs at a voltage level of 280 to 41 V. The fuel cell itself runs at a voltage level of 40 to 90 V.

System	Min voltage (V)	Max voltage (V)
EV	280	410
FC	40	90

To adapt the voltage levels the traction DC/DC-converter is added between the two subsystems. This DC/DC-converter raises the voltage level from the fuel cell to the EV with a corresponding reduction in the current. As these voltage levels are not common for any usual DC/DC-converter application we were only able to find one converter that could serve our needs. This converter is from the company Brusa in Sennwald. Unfortunately this converter is designed for a maximum power which is more than 10 times that we need.

The DC/DC-converter is mounted at the very top of the “engine” compartment. The rest of the traction system is mounted below it. It is hinged at one side so that it can be swung up without disconnecting and cabling to be able to access the parts below it.

The DC/DC converter is liquid cooled and its back side is a cooling plate. Some other smaller electrical units that also need to be cooled, such as the high voltage battery charger and the compressor controller, are mounted on this cooling plate to be able to profit from the cooling circuit.

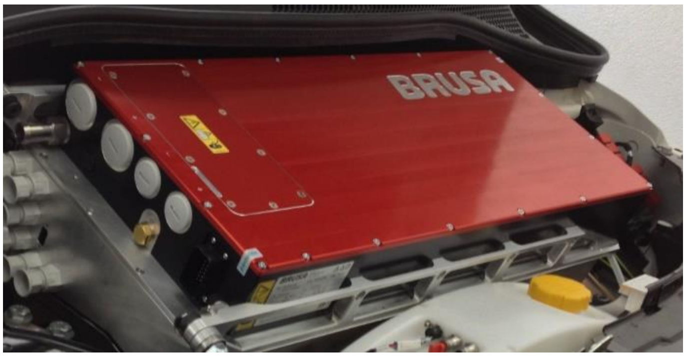


Fig. 17: The 110 kW DC/DC-converter supplied by Brusa.

Fig. 18: The DC/DC-converter swung up with the different electronic modules mounted on its back cooling plate. There is a waterproof cover mounted over the back of the DC/DC during use.

3.3 User interface

A user interface was created using unassigned buttons available in the Fiat 500. These are seen in the photo below.

Button	Function
FC	Start / Stop the FC
HSL	Resets the HSL for filling
LED	Indicates the FC state

The usage of the FC is as follows:

1) When the FC is off (LED off) pressing the button FC initiates the start procedure. The LED blinks slowly until the FC is running and then remains on.
   If the battery is above 85% the FC remembers to “turn-on order” but does not start until the battery state of charge (SOC) descends below 85%. During this time the LED blinks irregularly.
2) When the FC is on (LED on) pressing the button FC initiates a stop procedure, the LED blinks slowly until the FC is completely off.
3) If the FC encounters an error that causes an emergency stop the LED blinks quickly until the FC is completely off.

Fig. 19: User interface using unassigned buttons available in the Fiat 500.

3.4 Hardware safety layer

The HSL is an independent monitoring layer that controls the opening of the hydrogen valve at the hydrogen tank. In that case of over temperature or detection of hydrogen in the vehicle this valve is automatically closed. Before the FC can be used it must be reset.

The usage of the HSL (Hardware Safety Layer) is as follows:

1) Pressing the FC Button resets the HSL
2) Pressing the HSL button resets the HSL
   This button is necessary to reset the HSL and open the hydrogen valve for filling the H2 tank without starting the FC.

3.5 Driver's Information

A driver information unit was created displaying critical and interesting information for the driver of the vehicle. This information is:

- Gear state (Drive, Reverse, Neutral)
- Driving mode (Eco, Normal)
- Battery State of Charge (SOC)
- Hydrogen filling level
- Actual power coming from the battery (or entering in the battery if the value is negative)
- Actual power coming from the fuel cell

Fig. 20: Special display to give essential information's to the driver.

3.6 Cabling

The rest of the electrical adaptation is mostly cabling. There is high voltage cabling between the EV battery pack and the DC/DC converter. Low voltage cabling connects the communication bus of the EV with the FC system as well as the added sensors in the vehicle and safety system. The connections between the EV and the FC system are mostly made in two junction boxes. These boxes are mounted under the hood between the DC/DC and the Inverter.

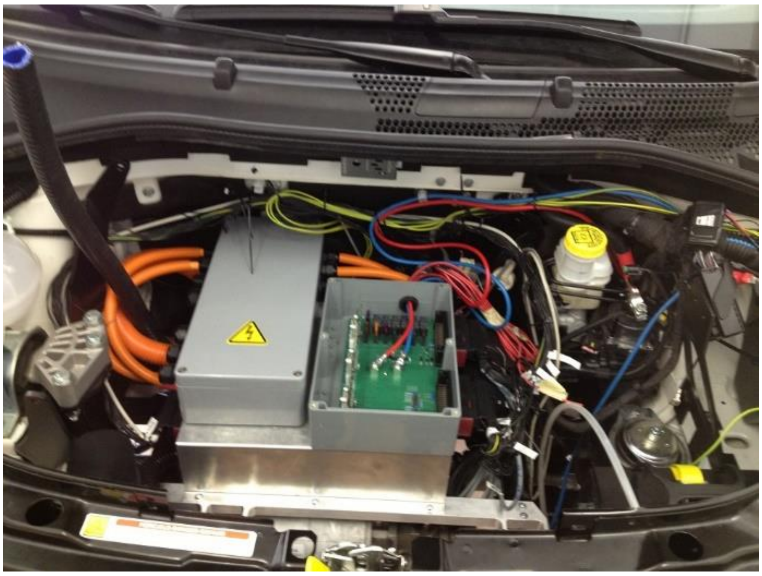


Fig. 21: Junction boxes. The box on the left is for the high voltage connections and fuses. The box on the right is for the low voltage connections.

4. Fuel cell operation strategies

4.1 Control strategies for the fuel cell hybrid powertrain

Three control strategies have been implemented and tested in the vehicle. These strategies control the fuel cell power delivered to the 400V bus according to an objective (i.e. reducing the hydrogen consumption, minimize battery stress) while respecting constraints on the battery pack and the fuel cell system (minimum and maximum powers, state of charge).

The control strategy problem can be formulated as follow:

System	$P_{trac} = P_{fcs} + P_{batt}$	with	P_{trac} the power demand P_{fcs} the fuel cell system power P_{batt} the battery pack power
Objective	$Min_{Pfcs}\ f(P_{fcs},X)$	with	X the system state
Constraints	$0 < P_{fcs} < 10$ kW $10\% < SOC < 90\%$ -16 kW $< P_{batt} < 60$ kW	with	SOC the battery state of charge

4.2 Strategy 1: Fixed fuel cell operating points

The objective of this strategy is to reduce the stress on the fuel cell system by selecting 3 operating points (Figure 22). Switching between the 3 operating points is made according to the motor power demand:

- Point 1: Throttle released / No power demand
  - Battery charges at 3 kW;
  - Reduced noise level.
- Point 2: Throttle pressed / Middle power demand (> 6 kW)
  - Driving at low/medium speed;
  - Battery used as energy buffer (charge and discharge).
- Point 3: Throttle pressed / High power demand (> 9 kW)
  - Driving at medium/high speed or uphill;
  - Full fuel cell power directly used for traction.

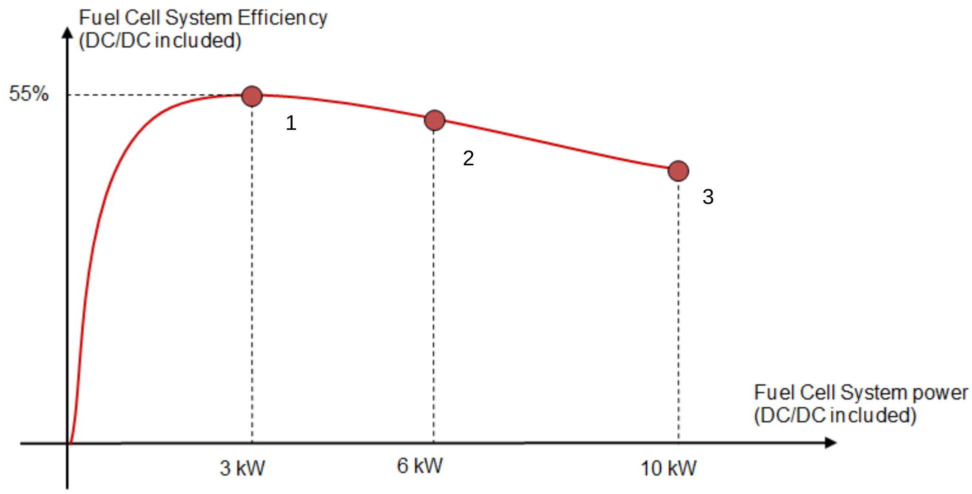


Fig. 22: Fuel cell system operating points in Strategy 1.

4.3 Strategy 2: Load following

In this strategy, the objective is to minimize the stress on the battery. The fuel cell power follows the motor power demand up to 10 kW (Figure 23). The battery provides the additional power during transient and power demand higher than 10 kW.

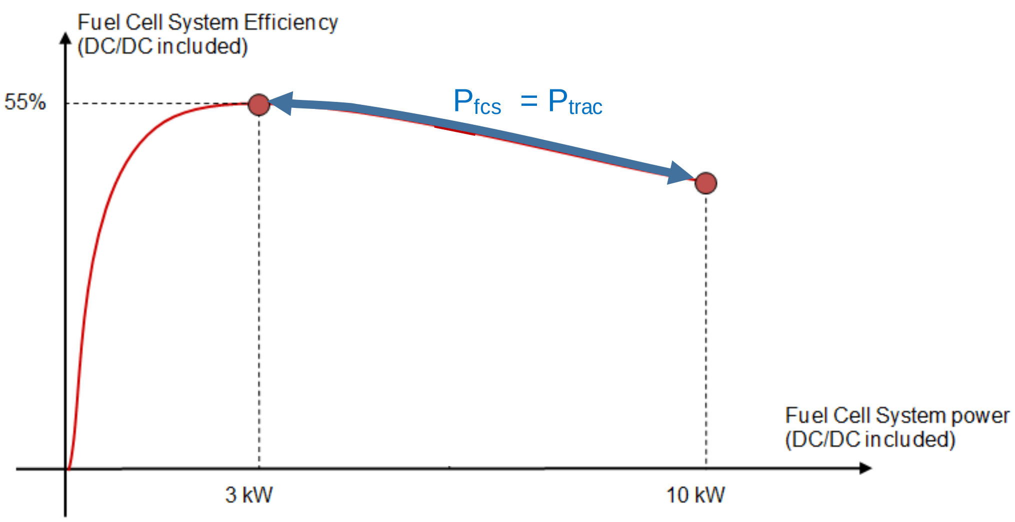


Fig. 23: Fuel cell system operating line in Strategy 2.

4.4 Strategy 3: Battery recharge

In this strategy, the objective is to charge the battery with the fuel cell system. The fuel cell power is set constant to 10 kW (Figure 24). The battery can be charged up to 10 kW if there is no power demand of the traction. This strategy is used when the battery SOC is low (below 20%) and the driver needs to enhance the range to reach his/her destination. This strategy can be activated by the driver at any time when he/she sees fit. As such it is running in parallel with the strategy 2 in the vehicle.

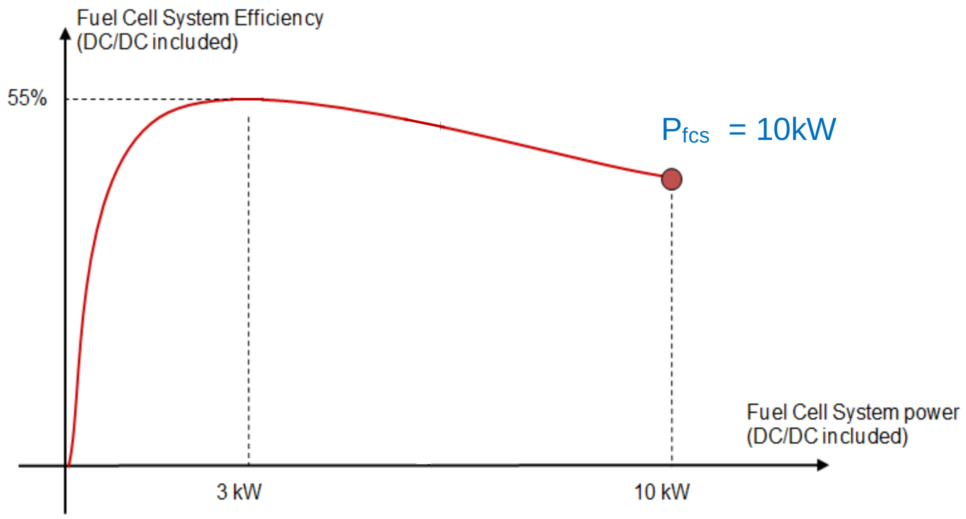


Fig. 24: Fuel cell system operating point in Strategy 3.

4.5 Comparison of strategies

The first strategy has been tested for 3 months.The second and the third strategy have been tested together for 3 months.

Strategy	Duration of the test
1	From 15.08.2013 to 17.11.2013
2 & 3	From 18.11.2013 to 01.03.2014

Below we can see the statistics taken from the driven mileage of the car. The row labelled "Totals" above the labels is the value over the entire time period, below that are the weekly results. The Table 2 shows the results from the time during which Strategy 1 was used.

Statistics - Kamoo Fiat500e with Belenos Range Extender

Read Data Files | Start Date 15.08.2013 | End Date 17.11.2013 | Today | dd.mm.yyyy

Directory N:\1. Projects\1029_Demo_Fiat\LogFiles\

142.905 million CAN messages

1046 N:\1. Projects\1029_Demo_Fiat\LogFiles\13111700.txt

Week	KmTotal	AvgSpeed	VhOnTime	TOperatingFC	PFCstack	FCPaux	PDCDCin	PDCDCout	VerbrauchEl	VerbrauchH2	Dcout/Stack	Dcout/H2	Battery °C			Motor °C		FC °Cout			Speed	Deviation
KW	km	kmh	hrs	hrs	avg kW	avg kW	avg kW	avg kW	Wh/km	g/km	eff %	eff %	min	avg	max	avg	max	min	avg	max	max kmh	Vavg-Vmin
Totals	10056.98	47.34	212.43	82.44	7.85	0.42	7.17	6.76	187.61	13.42	86.8	41.9	4	24	45	55	140	4	59	84	135	
33	60.24	36.04	1.67	1.19	7.13	0.39	6.57	6.18	206.35	15.28	86.76	40.53	28	33	39	73	140	26	64	82	87	0.003
34	605.93	43.40	13.96	4.22	7.84	0.43	7.17	6.74	179.53	14.47	86.03	37.22	16	29	45	57	140	14	58	82	126	0.005
35	949.59	46.27	20.52	11.16	7.28	0.39	6.69	6.30	192.01	12.86	86.60	44.78	13	28	38	61	140	11	63	82	126	0.003
36	908.94	46.73	19.45	11.60	8.28	0.42	7.57	7.14	184.88	13.51	86.23	41.07	15	28	41	58	124	14	64	83	125	0.004
37	884.89	54.86	16.13	2.44	8.21	0.43	7.52	7.12	156.29	10.11	86.69	46.36	14	24	41	51	122	12	63	83	123	0.011
38	558.22	33.33	16.75	4.04	7.23	0.52	6.66	6.29	193.81	13.35	86.91	43.54	11	22	35	39	140	14	45	84	131	0.001
39	853.65	48.09	17.75	2.84	6.78	0.40	6.24	5.79	189.88	17.91	85.28	31.82	12	27	44	61	140	10	50	84	129	0.008
40	410.65	38.96	10.54	0.31	6.54	0.49	6.03	5.65	191.71	23.83	86.39	24.14	14	25	39	54	113	16	27	80	123	0.003
41	443.56	47.34	9.37	3.71	7.84	0.42	7.17	6.75	194.69	13.62	86.07	42.89	13	24	33	58	132	11	56	83	125	0.005
42	1197.97	50.35	23.79	8.03	7.75	0.51	7.20	6.81	166.84	11.30	87.88	44.28	12	21	34	50	140	11	57	83	135	0.006
43	145.40	30.78	4.72	0.52	5.15	0.36	4.70	4.29	179.95	9.67	83.33	55.82	15	21	28	42	90	16	56	82	117	0.001
44	581.10	50.47	11.51	5.97	8.07	0.40	7.33	6.91	203.38	16.26	85.55	37.52	9	21	32	62	140	7	61	84	129	0.010
45	1260.81	54.88	22.97	10.35	8.76	0.46	7.90	7.44	194.98	16.21	85.02	36.08	9	21	34	60	140	8	59	83	127	0.012
46	1196.01	51.36	23.29	16.06	7.78	0.34	7.07	6.67	210.24	12.47	85.73	50.58	4	19	38	56	127	4	67	83	123	0.011

Table 2

As we can see the average hydrogen consumption pro km (VerbrauchH2) is 13.42 grams.

Table 3 shows the results from the time during which the Strategies 2&3 were used.

Statistics - Kamoo Fiat500e with Belenos Range Extender

Read Data Files | Start Date 18.11.2013 | End Date 01.03.2014 | Today | dd.mm.yyyy

Directory N:\1. Projects\1029_Demo_Fiat\LogFiles\

139.747 million CAN messages

961 N:\1. Projects\1029_Demo_Fiat\LogFiles\14022008.txt

Week	KmTotal	AvgSpeed	VhOnTime	TOperatingFC	PFCstack	FCPaux	PDCDCin	PDCDCout	VerbrauchEl	VerbrauchH2	Dcout/Stack	Dcout/H2	Battery °C			Motor °C		FC °Cout			Speed	Deviation
KW	km	kmh	hrs	hrs	avg kW	avg kW	avg kW	avg kW	Wh/km	g/km	eff %	eff %	min	avg	max	avg	max	min	avg	max	max kmh	Vavg-Vmin
Totals	10481.92	49.32	212.54	106.40	7.16	0.37	6.61	6.23	215.08	11.99	86.1	53.8	0	16	38	52	127	0	61	86	126	
47	849.67	47.84	17.76	9.21	6.52	0.34	5.99	5.61	213.77	12.23	86.12	52.44	3	15	33	51	110	3	62	85	121	0.011
48	846.84	45.55	18.59	9.76	7.87	0.40	7.25	6.84	221.86	12.26	86.97	54.30	0	15	32	48	102	2	62	86	124	0.020
49	1098.96	53.32	20.61	11.88	8.51	0.38	7.87	7.46	219.91	16.89	87.57	39.07	0	17	34	57	116	6	68	84	126	0.023
50	859.97	53.22	16.16	8.37	6.49	0.35	6.11	5.74	225.21	13.55	88.52	49.88	0	17	33	55	107	0	58	84	125	0.015
51	753.47	53.94	13.97	6.81	8.49	0.39	7.84	7.42	216.43	5.39	87.43	120.47	0	14	32	54	106	3	61	83	125	0.028
52	943.60	57.62	16.38	8.61	8.49	0.37	7.82	7.40	215.43	16.03	87.23	40.31	3	18	35	59	127	5	62	83	123	0.034
1	542.05	50.32	10.77	3.75	7.02	0.33	6.60	6.21	217.24	15.86	88.50	41.10	2	13	27	49	105	4	50	82	123	0.036
2	834.90	59.94	13.93	7.92	7.62	0.27	7.15	6.76	202.43	12.98	88.72	46.78	2	17	33	59	125	4	62	82	123	0.050
3	167.03	32.14	5.20	2.34	6.16	0.38	5.73	5.37	221.95	16.23	87.19	41.03	3	16	21	40	75	3	59	82	111	0.045
4	761.79	42.03	18.13	9.45	7.19	0.43	6.55	6.18	211.22	5.47	85.97	115.83	2	16	35	47	113	6	60	82	121	0.054
5	897.51	46.66	19.23	7.69	7.41	0.42	6.74	6.38	204.26	15.86	86.15	38.64	2	16	27	49	109	3	58	81	125	0.072
6	575.00	50.16	11.46	5.50	7.18	0.40	6.48	6.14	218.66	1.21	85.49	541.50	3	16	29	54	122	4	61	80	123	0.082
7	893.11	59.37	15.04	5.62	6.35	0.39	5.77	5.45	203.19	14.32	85.83	42.57	4	17	38	57	114	5	60	80	123	0.079
8	458.01	29.93	15.30	9.50	4.02	0.36	3.74	3.45	235.74	6.59	85.94	107.30	2	19	31	42	104	5	60	80	123	0.057
9																						

Table 3

Here we see an average hydrogen consumption pro km (VerbrauchH2) of 11.99 grams, an improvement of 11%. This improvement is, however, probably not entirely due to the hybrid strategy change. At the same time some parameters of the fuel cell itself have been changed such as the amount of humidification and the stoichiometry. These parameters also have an influence on the efficiency of the fuel cell.

5. Real road testing

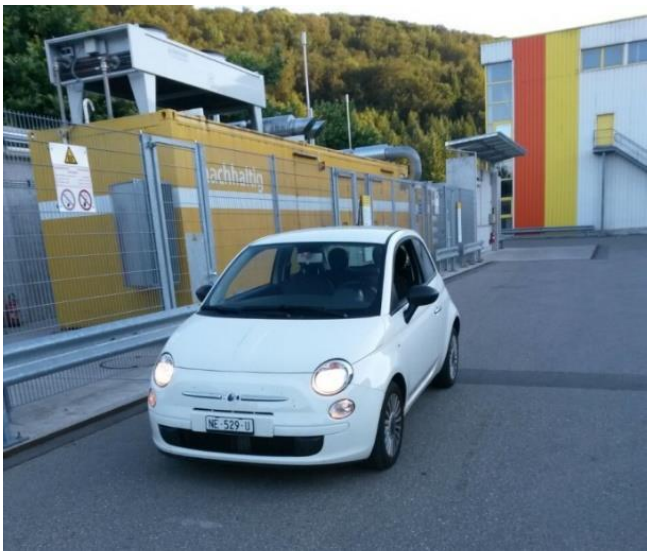
5.1 Road testing at PostAuto

During the 2 weeks from July 7th to July 21st 2014 the vehicle was tested at PostAuto in Brugg. This was the ideal testing place for us as it is the only place outside of Belenos in Switzerland where we can have simple access to hydrogen for filling.

We gave the people from PostAuto no limitations on the use of the vehicle other than the fuel cell should be started whenever the vehicle is in use. The vehicle battery was charged every evening and hydrogen tanked at the Post Auto hydrogen filling station when needed.

Mr Huber, the responsible of Post Auto in Brugg, gave us the following short report:

> Wir von der Postauto Voegtlin-Meyer aus Brugg durften während 14 Tagen einen Fiat 500 mit der Brennstoffzellen Technologie fahren. Zurzeit betreiben wir zudem 5 Postautos mit der gleichen Technologie. Für uns war es sehr spannend die Fahrzeuge zu vergleichen.
> Es waren 28 Personen die das Fahrzeug getestet haben. Alle Personen hatten nicht ein Problem mit dem Fahrzeug. Auch die Handhabung ist sehr einfach und verständlich. Das Fahrverhalten ist optimal. Einziger Unterschied in den ersten Sekunden gegenüber einen Benzin Auto ist, dass das Motorengeräusch vermisst wird und anfänglich ist schwer merkbar, wie das Gas reagiert. Dies hat aber einen Vorteil im Fahrkomfort da es sehr leise ist.
> Der Einsatz war auf Autobahnen, Landstrassen und Nebenstrassen mit Gefällen und Steigungen. Keine der 28 Personen hat sich über ungenügende Leistung beklagt.
> Wir bedanken uns für die Möglichkeit, dass wir ein solches Zukunftsfahrzeug testen durften.
> ******************************
> **Reto Huber**
> Geschäftsführer
> Post Auto
> Voegtlin-Meyer AG
> Wildischachenstrasse 6
> 5200 Brugg



The hydrogen Fiat 500e at the PostAuto hydrogen filling station in Brugg

StatisticsCANF3-PostAuto21-07-2014.xlsm:2

Statistics - Kamoo Fiat500e with Belenos Range Extender

Read Data Files | Start Date: 07.07.2014 | End Date: 21.07.2014 | Today | dd.mm.yyyy

Directory: N:\1. Projects\1029_Demo_Fiat\LogFiles\

43.238 million CAN messages

331 N:\1. Projects\1029_Demo_Fiat\LogFiles\14072100.txt

Week	KmTotal	AvgSpeed	VhOnTime	TOperatingFC	PFCstack	FCPaux	PDCDCin	PDCDCout	VerbrauchEl	VerbrauchH2	Dcout/Stack	Dcout/H2	Battery °C			Motor °C		FC °Cout			Speed	Deviation
KW	km	kmh	hrs	hrs	avg kW	avg kW	avg kW	avg kW	Wh/km	g/km	eff %	eff %	min	avg	max	avg	max	min	avg	max	max kmh	Vavg-Vmin
Totals	2342.65	36.94	63.42	26.65	6.16	0.38	5.72	5.32	182.23	13.45	86.8	40.7	15	29	49	59	130	15	59	84	125	
28	1239.46	40.45	30.64	12.65	6.44	0.37	5.98	5.59	174.82	12.81	86.81	40.95	15	27	41	57	106	15	60	83	122	0.005
29	927.95	32.20	28.81	11.12	5.39	0.40	5.01	4.60	192.66	14.59	85.41	39.63	20	31	49	61	130	21	55	84	125	0.003
30	175.24	44.20	3.96	2.87	7.95	0.33	7.36	6.95	179.38	12.70	87.34	42.38	18	23	26	52	84	17	73	83	113	0.013

Display | Accumulated | Output | Definitions | Polarisation | PolarisationInitial (2) | WarningList | Graphs

StatisticsCANF3-PostAuto21-07-2014.xlsm:1

Week	KmTotal	VhOnTime	FConTime	FCstack	FCPaux	DCDCin	DCDCout	H2%Used	Bat %	Bat Ah	Bat Energy	FC	Starts	FC	Stops	Starts	Starts	NrWL2	NrWl3	kg H2	kWh H2	Vmax>0.9	
KW	KmTotal	hrs	hrs	kWh	kWh	kWh	kWh	%	%	Ah	kWh	starts	OK	Stops	OK	<40°C	<2°C			kg	kWh	%time	Hrs
Totals	2342.6	63.4	26.6	164.3	10.0	152.5	141.9	616.0	1043.0	681.7	285.0	118	120	102	57	64	0	390	2	10.5	349.0	3.16	
28	1239.46	30.64	12.65	81.51	4.67	75.66	70.77	305	530	354.93	145.91	62	62	53	29	34	0	183	1	5.19	172.82	3.57	
29	927.95	28.81	11.12	59.94	4.44	55.75	51.19	228	475	304.61	127.58	46	48	41	24	27	0	199	1	3.88	129.19	3.18	
30	175.24	3.96	2.87	22.82	0.94	21.11	19.93	83	38	22.13	11.50	10	10	8	4	3	0	8	0	1.41	47.03	1.25	

Display | Accumulated | Output | Definitions | Polarisation | PolarisationInitial (2) | WarningList | Graphs

As always our data logger was working the whole time and gave us valuable information about the working of the fuel cell and the vehicle. The statistics for the two weeks can be seen in the tabele on the previous page.

Notice that over 2000 km where driven in the two weeks and the average power consumption was 182.2 W/km. The fuel cell was running about 30% of the time, this although the fuel cell was turned on by the drivers at every start. This can be explained by 2 factors.

1) The start of the fuel cell is delayed until the battery SOC is below 85%. This is so that braking energy can be recovered in the battery even when the fuel cell is running which is not possible when the battery is full. As the battery was fully charged every evening, each day started running pure electrically until the battery SOC was below 85%.
2) In the log files it can be seen that the fuel cell did not always start correctly. We have found that this is because of an unreliable sensor. This sensor for the fuel cell coolant level was often showing an insufficient coolant level. This was causing errors during the fuel cell start-up procedure. Once the fuel cell was working, however, all was well.

Except for this sensor error the fuel cell ran without problems as did the rest of the vehicle. The driving statistics don’t show any major differences in comparison to our usage.

5.2 Real testing of the vehicle range

We used the on-board data acquisition system to monitor all the parameters that are relevant to judge if our fuel cell system performs well as a range extender for a battery vehicle. As already mentioned in Table 1, the usable on-board energy is 26 kWh from the 210 kg battery pack plus an estimated 26 kWh coming from the conversion of the 1.7 kg hydrogen stored in the high pressure tank.

When we plot over time the SOC of the battery with the vehicle speed, the hydrogen level, the battery power and the fuel cell power, one can see that the 10 kW fuel cell acts as a perfect range extender (see Fig: 25). When the vehicle drives at high speed (>100 km/h) on the highway, the battery SOC and the hydrogen level decrease at the same rate. When the vehicle drives on country roads (80 km/h), the average energy brought by the fuel cell compensate the average consumption and the SOC of the battery stays flat. When the vehicle drive in cities (<50 km/h), the average energy brought by the fuel cell recharges the battery.

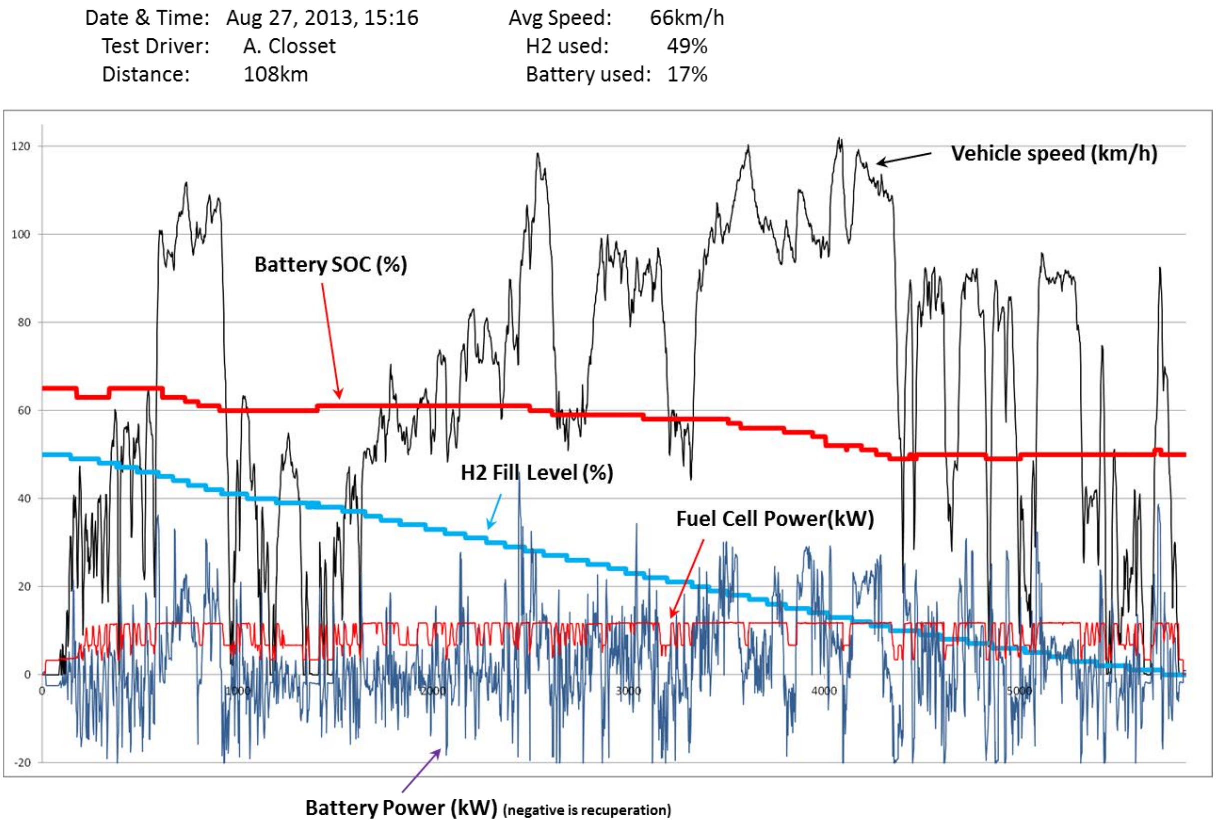


Fig. 25: Real on-road driving showing the positive performance of the fuel cell range extender on the battery SOC of the electric vehicle.

These results prove that the chosen vehicle architecture (Fig: 26) is absolutely ideal for an electric vehicle that will drive every day on Swiss roads, with a mix of highway, city driving and national roads.

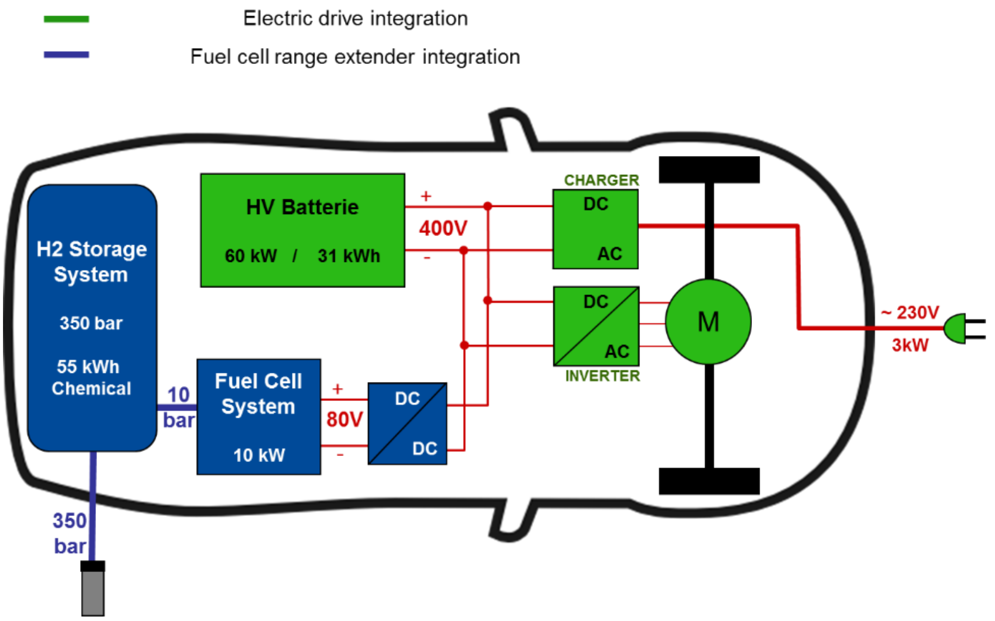


Fig. 26: Electric vehicle architecture with a 10kW fuel cell range extender

A record range of 425 km was demonstrated with the “Eco mode” but normal driving conditions, thus proving that the developed fuel cell range extender can double the range of a normal battery vehicle with only 1.7 kg of on-board hydrogen (see Fig: 27).

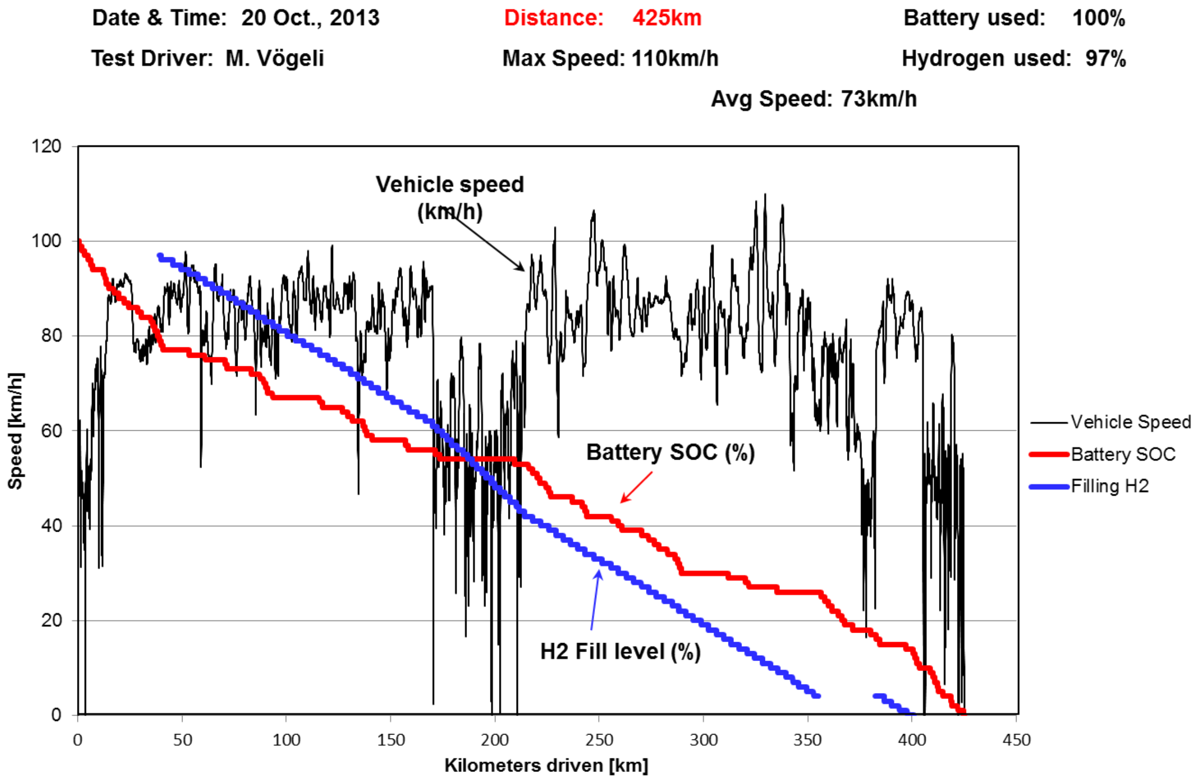


Fig. 27: Record range of 425 km realized with battery SOC going from 100% to 0% and the hydrogen level going from 97% to 0%.

5.3 Statistics over 27 months and 90,000 km

Complete data recording over the entire project time has proved to be an invaluable aid in debugging and optimization of the vehicle. As all the communication on the internal CAN bus of the vehicle is recorded permanently even events that occurred early in the life of the vehicle can be re-constructed. This has allowed us, for example, to reconstruct that there have been 148 overvoltage events on the traction inverter since the vehicle was first commissioned. This is an error that we have only recently been interested in, but having a complete record has allowed us to now investigate that which happened in the past. At present the log files take a storage of 43 Gigabyte.

Following are the weekly statistics from 15.08.2013 to 13.11.2015. Such things as the evolution of the cell voltage deviation, one of our best indications for stack degradation, can be easily followed (V_{avg}–V_{min}). All those error signals can be plotted in a error pie chart showing the frequency of the errors that have caused the fuel cell to shut down. These are, of course, raw data and do not directly indicate the reason why the error occurred. There are, for example, many reasons why the cell voltage could be in error, a compressor failure is one reason, for example.

With these statistics it has been possible to determine error sources and critical components and their progression over the lifetime of the vehicle. Fig: 28 shows an example of such error pie chart.

Error Code	Count	
256	2	Cmp temperature
16384	163	Cell voltage
8192	13	Stack temperature
268435456	15	DCDC BRUSA error
2097152	62	Coolant level
536870912	42	H2 tank level
65536	11	Coolant inlet temperature
262144	7	Coolant delta temperature
33554432	62	H2 tank pressure
131072	5	Coolant outlet temperature
1024	10	Anode pressure
32768	255	Cell deviation
49152	1	Cell deviation
8388608	9	H2 tank temperature
1	6	External ES
64	1	Air flow control
32	2	Stop duration

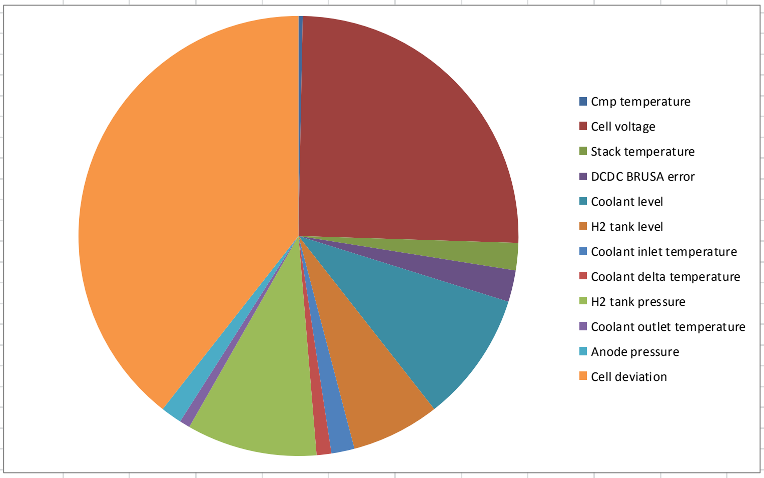


Fig. 28: Example of an error pie chart deriving from on-board recording statistics.

A resume of the global statistics of the real on-road driving over almost 90,000 km is shown in Table 4. It is very interesting to highlight the following points:

- Thanks to the electric motor, the drivetrain consumption has an equivalent of 2liter gasoline per 100 km.
- The average power demand of the electric motor is 9.4 kW, matching perfectly the power delivered by the fuel cell.
- The fuel cell range extender is used about 50% of the time, thus reducing the number of battery full cycles that would be required to do the same amount of km.
- The battery full cycles amount to around 450 instead of estimated 700 full cycles for the same amount of kilometer driven without the range extender.
- The tank to motor efficiency amount to 41% of hydrogen conversion.

What	Value
Distance	87‘109 km
Average speed	57 km/h
Drivetrain consumption	191 Wh/km, (= 2.2$L_{essence}$/100km)
Vehicle ON time	1770 h
Average power demand	9.4 kW
Battery full cycles	446
Fuel cell ON time	830 h (47% of vehicle ON time)
Fuel cell average power	7.1 kW
H_2 total consumption	366 kg
Number of FC starts	2662
Average efficiency H2 tank to DC bus (including Stack, BoP, Purges, DC/DC)	41 %

Table 4: Full statistics of the hydrogen Fiat 500e over almost 90,000 km.

6. Conclusion

The fuel cell vehicle has, on the whole, been remarkably reliable and has up ‘til now absolved over 90,000 km in just over t years. Approximately half that distance has been run using energy from the fuel cell. The other half using electricity charged from the grid.

Certain components, such as the compressor bearings, were known from the beginning to be inadequate for the application even if they were much worse than planned. After the initial debugging and shake-out, where problems such as the coolant tank came to light, the fuel cell system itself rarely caused a problem. Most of the problems were caused by the vehicle around the fuel cell system and were, as such, not among the objects of this project.

This project has been a major step in proving the reliability of a fuel cell system in a vehicle application. It has shown exactly where the future development goals must lie, i.e. in the fuel cell system management, the stack membrane lifetime and compressor bearing lifetime goals.