GIANTLEAP

DELIVERABLE D6.3

PUBLIC

Results from demonstration of the range extender

FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

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Project acronym: GIANTLEAP

Project title: GiantLeap Improves Automation of Non-polluting Transportation with Lifetime Extension of Automotive PEM fuel cells

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Abstract: Within the scope of GiantLeap project, Bosch Engineering GmbH, together with VDL Enabling Transport Solutions b.v. and their partners, designed and built a fuel cell range extender system for battery electric buses. This system is contained in a specially designed trailer to be attached to the tow hitch of any suited electric bus. Depending on a power demand sent by the vehicle, the fuel cell system generates the power needed for the propulsion of the vehicle as well as charge the vehicle's traction battery. Two full size systems have been built, commissioned and tested on BEG's system test bench and the trailer module respectively, and calibrated to be operated on public roads. Due to various issues that occurred during calibration and testing, an originally planned final endurance test hat to be cut short to finish the project in time.

Revision History

Date	Description	Author
11/21/2019	Draft Version 0.1	Peter Eckert
11/28/2019	V 0.2: Implement internal corrections	Peter Eckert
12/09/2019	V 0.3: Changes proposed by ElringKlinger	P. Eckert / Stefan Hemmer
12/11/2019	V 1.0: Final version after QA	P. Eckert / Ruud Bouwman

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1 Introduction

1.1 Document overview

Work package 6 contains the consolidation of the work done in the previous work packages to design and build a working prototype of a PEM fuel cell range extender. In the GiantLeap proposal the definition reads:

"WP6: Prototype will comprise the construction of a range extender powered by hydrogen fuel cells. The range extender will be tested in an emulated relevant environment with long-term and accelerated tests. Robust hybridization strategies will be developed to interface buses with range extenders." (1)

After the design of the fuel cell system (WP5.2), commissioning on the test bench and delivery to VDL ETS (WP5.4), and build of the range extender module (WP6.2), focus of WP6.3 was the commissioning of said REx module with the vehicle, testing under relevant conditions, collection, and evaluation of measurement data.

1.2 Background and project context

Within WP5 BEG selected and purchased all BoP components to integrate the full size stacks provided by ElringKlinger through WP4 into a complete fuel cell system. After commissioning and pre-calibration of the FCCU controller (focus of WP3) on the test bench, the completed system was delivered to VDL ETS, mounted in a REx trailer, and connected to a test vehicle under the objective of WP6.

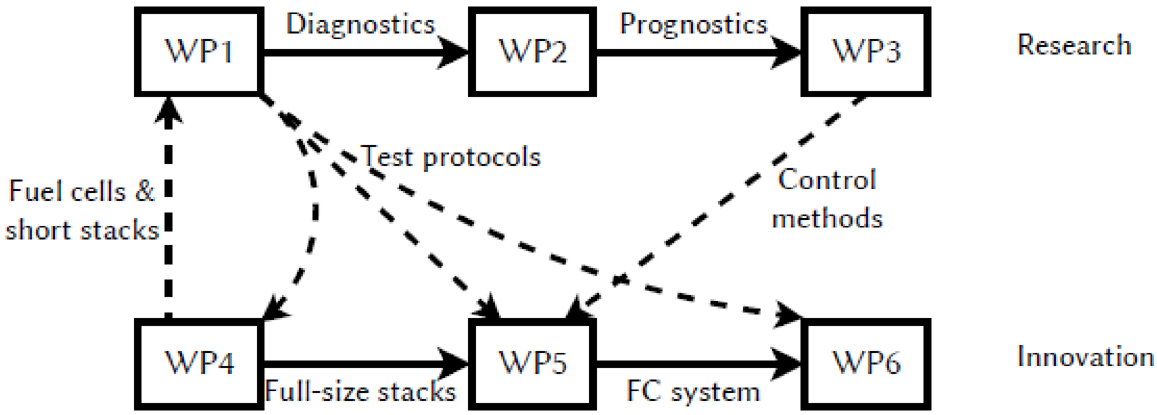

Fig. 1: Inter-action of the different work packages within GiantLeap project (1)

As described in the WP5.2 report (2), BEG engineers designed the fuel cell system under consideration of the results provided by work packages WP1 and WP2, also taking into account the limitations given by ElringKlinger (integrated anode path) and VDL ETS (tank system, vehicle interfaces, cooling system). Fig. 2 shows the general layout of the FC system and main interfaces.

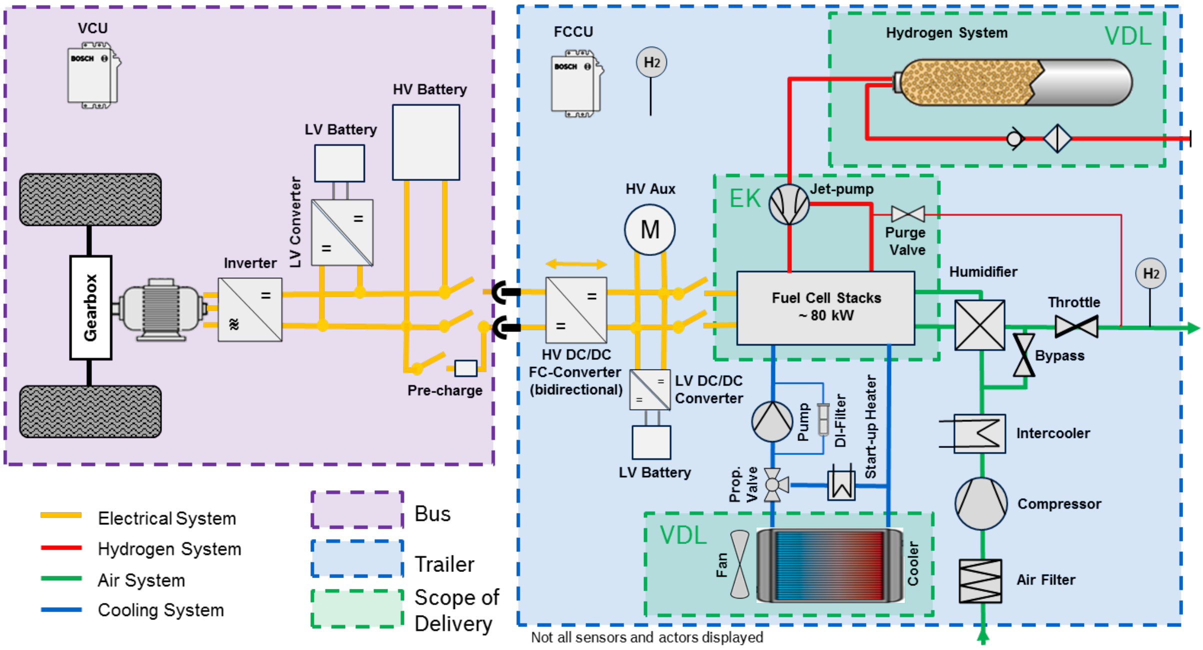

Fig. 2: FC System overview (2)

To control the FC system, BEG developed a fuel cell control unit (FCCU) suited for automotive use. The FCCU is based on a platform hardware and software already available, augmented by control strategies engineered within WP1, WP2, and WP3, component drivers suitable for the components used, and interface functions implementing the demand of the vehicle controllers.

2 Test Bench Activities

2.1 Test Bench Set-Up

Throughout the first stages of the project, after simulations and theoretical considerations had been finished, BEG built and used a full size fuel cell system to run on their systems test bench. BEG testing facilities offer the capability for testing fuel cell systems up to 150kW electrical power. The laboratory and test bench provide all necessary safety features regarding hydrogen and electrical safety, so all development activities can take place from the earliest prototype stages. Hydrogen supply, cooling, high voltage (max. 150 A boost, 600 A buck @ 500 VDC), acquisition of measurement data, and a simulation of the vehicle CAN interface is also part of the test bench.

The system built for the test bench included all components up to the vehicle interface. Hydrogen supply and cooling was provided by the test bench, electrical interface was after the DC/DC converter for most of the measurements. Fig. 3 and Fig. 4 provide an impression and overview.

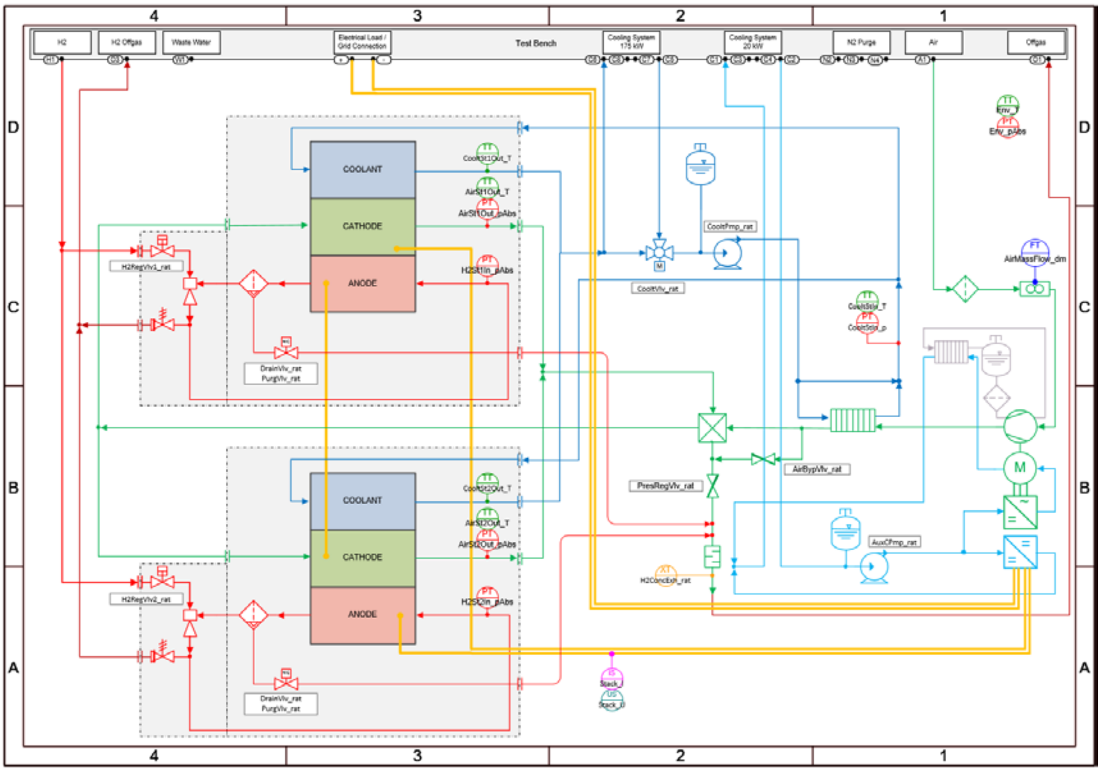

Fig. 3: Piping and instrumentation diagram of the test bench system

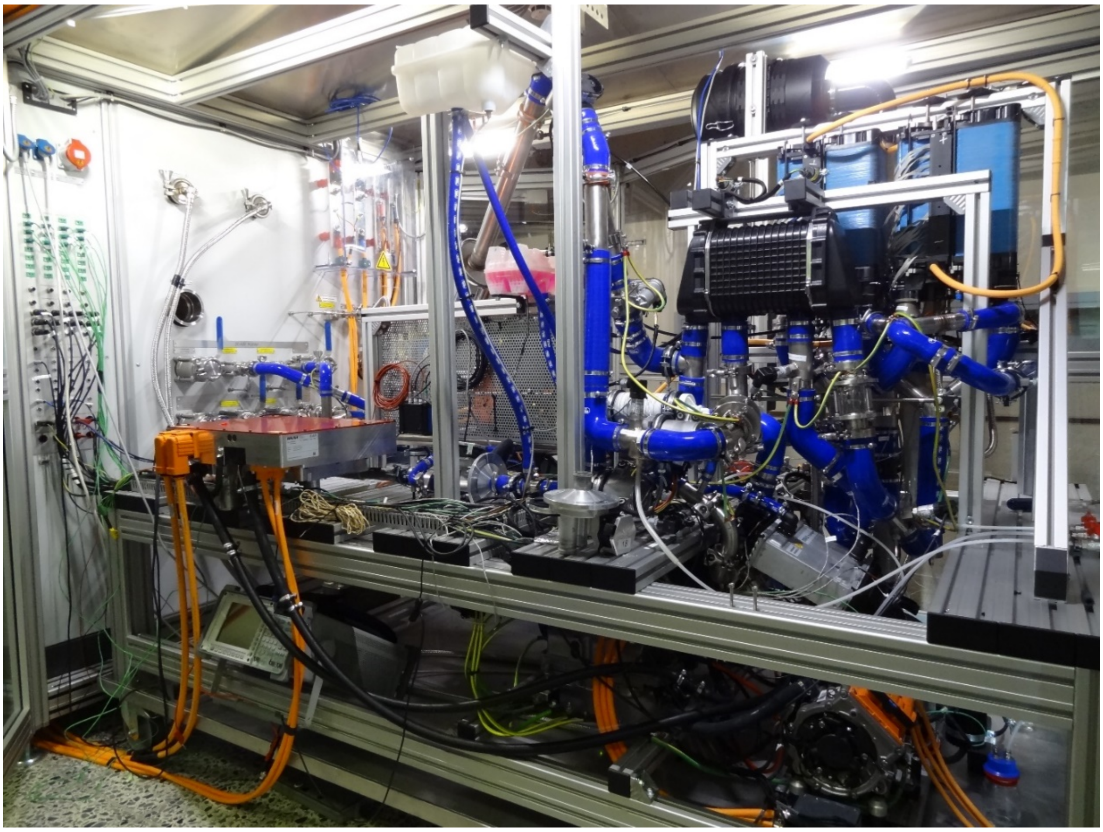

Fig. 4: Systems test bench

2.2 Characterization of Power Output

To verify the power output of the complete FC system in relation to the values measured with the stack only under optimum conditions on the stack test bench, polarization curves were measured at different stages of the project. ElringKlinger provided relevant reference values measured on their test bench under atmospheric operation and with a cathode air pressure of 1800 mbar$_a$, shown as the lower and upper red lines in Fig. 5 respectively.

The power output of the system in atmospheric operation is slightly higher than for the stacks only as measured on ElringKlingers' stack test bench. This shows that the system is working reasonably well according to the requirements of the stacks. As shown in Fig. 6, the cathode pressure in the system, even with membrane humidifier and muffler attached, is slightly lower than the values on the stack test bench. The cathode stoichiometry values as measured with the FCCU air flow meter however are higher, which explains the higher power output. In respect of a higher overall efficiency, further work should involve trying to reduce the lambda value for higher system power. For commissioning however, main focus was to ensure stable system operation, so air flow was kept a bit higher than strictly necessary.

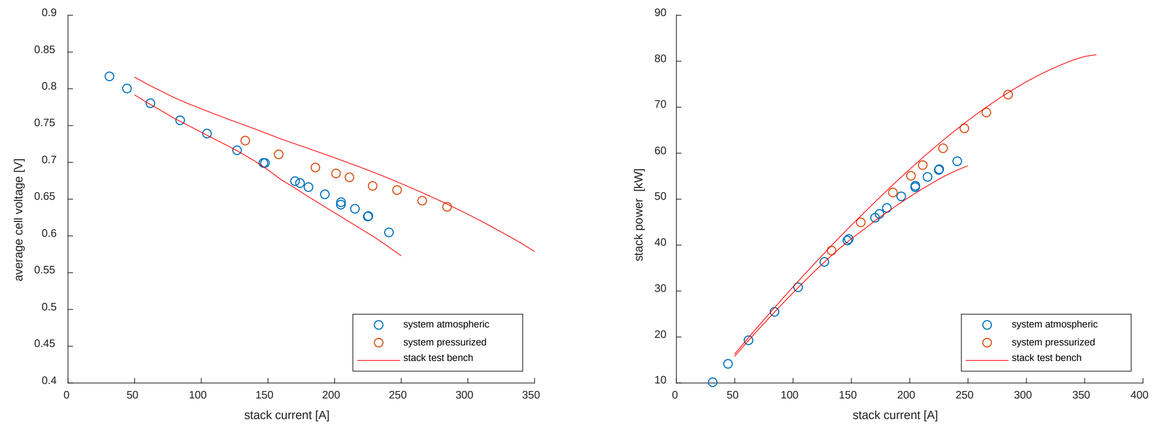

Fig. 5: Polarisation curves and power output of the system in relation to stack test bench results

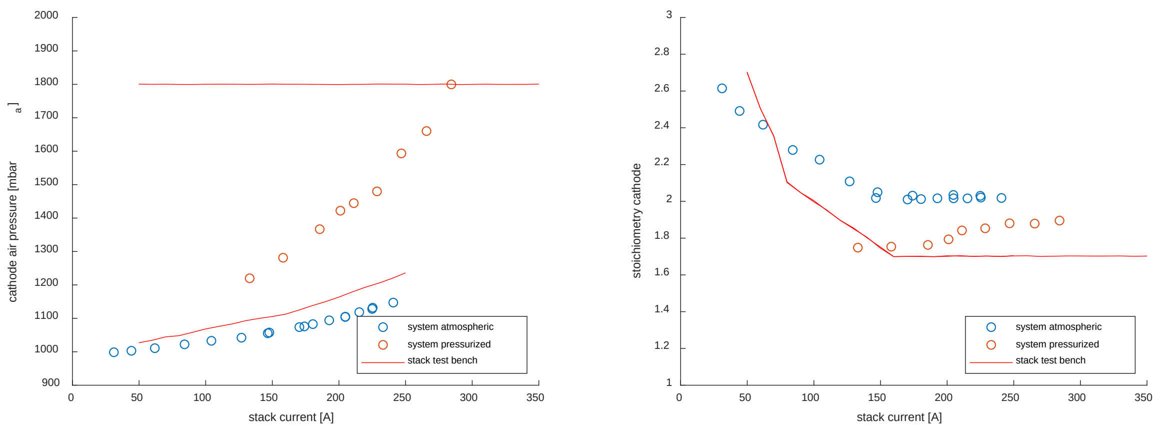

Fig. 6: Cathode pressure (left) and stoichiometry (right)

For pressurized operation, the power output generated by the system is slightly less than the reference values. As becomes evident from Fig. 5 and Fig. 6, with a turbo compressor attached, the reference cathode pressure can only be reached with a minimum airflow to avoid surging. Therefore, during the measurements, the cathode air pressure was below the reference value given by the stack test bench for the lower current values, which leads to a lower power output.

2.3 Pressure Dependency

The power any given fuel cell system can provide depends on the media supply pressure. The higher the pressure, the higher the stack output power. The left graph of Fig. 7 shows stack polarization curves measured on the BEG system test bench at various levels of cathode pressure. Those are framed by curves measured by ElringKlinger under ideal conditions on their stack test bench at atmospheric operation and 1800 mbar$_a$ respectively. The right graph displays the corresponding stack power.

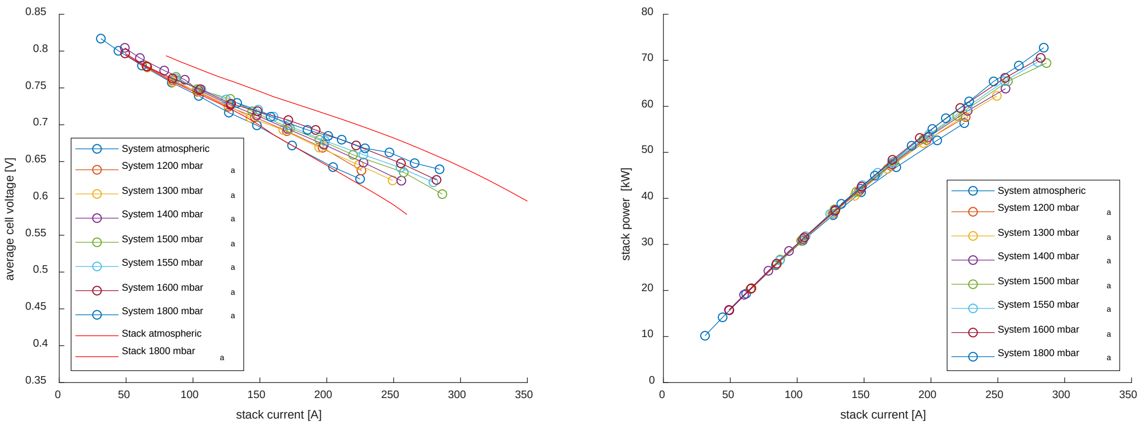

Fig. 7: Polarisation curves (left) and stack output power (right) at different levels of cathode pressure

On system level, depending on the components' physical layout, at some point the parasitic power losses necessary to generate the extra pressure will be higher than the additional power output. Hence, in terms of efficiency and net power output, there will be an optimum for each hardware set-up. As can be seen from Fig. 8, while the stack power is always rising with higher cathode air pressure, the system net power at 1800 mbar$_a$ (dark blue curve) is less that at 1600 mbar$_a$ (brown curve).

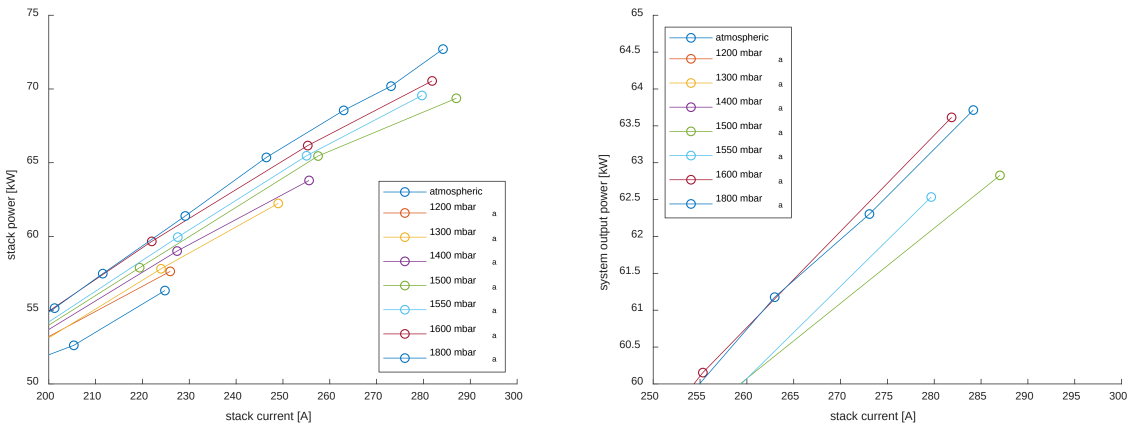

Fig. 8: Power output of the stack (left) vs. system net power (right)

The system net efficiency plotted against the cathode pressure (Fig. 9) clearly shows an optimum at about 1.7 bar_a for the current setup. The calibration for the pressure set point was adjusted accordingly. The right side of Fig. 9 shows the increasing power demand of the air compressor with raising cathode pressure.

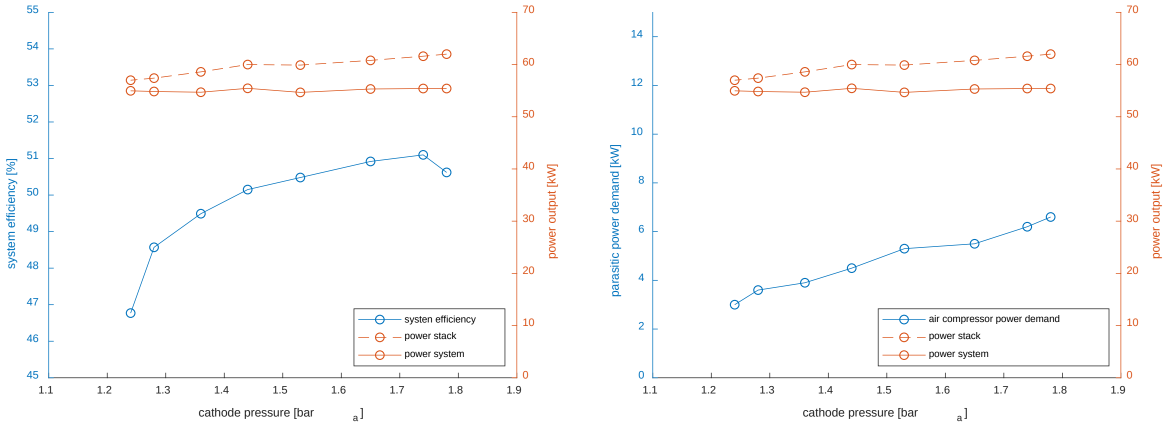

Fig. 9: System efficiency (left) and parasitic power demand (right) depending on cathode pressure

3 Vehicle Set-Up

3.1 Description

After BEG finished the calibration phase on the test bench, VDL ETS received all relevant components as reported in D5.4 (3). VDL mechanics then completed a trailer module, including hydrogen tanks with a capacity of about 30 kg and the main cooling system. To demonstrate the range extenders capabilities on the road, VDL ETS provided a 12 m battery electric bus of the type Citea SLF Electric. The vehicle was modified with tow hooks, data communication via automotive CAN bus and a high voltage connection to provide the power produced by the range extender to the traction batteries. Since the FC-system uses power from the vehicle's batteries during start up, the existing HV interface had to be modified to provide a bi-directional power flow. In addition, since the interface used is based on a standard charging protocol, the vehicle is now allowed to move even during charging, which obviously should not be possible when the vehicle is pugged to a charging station instead of the FC range extender.

Fig. 10 and Fig. 11 below provide an impression of the finished vehicle.

Fig. 10: VDL Citea test vehicle with GiantLeap FC range extender trailer

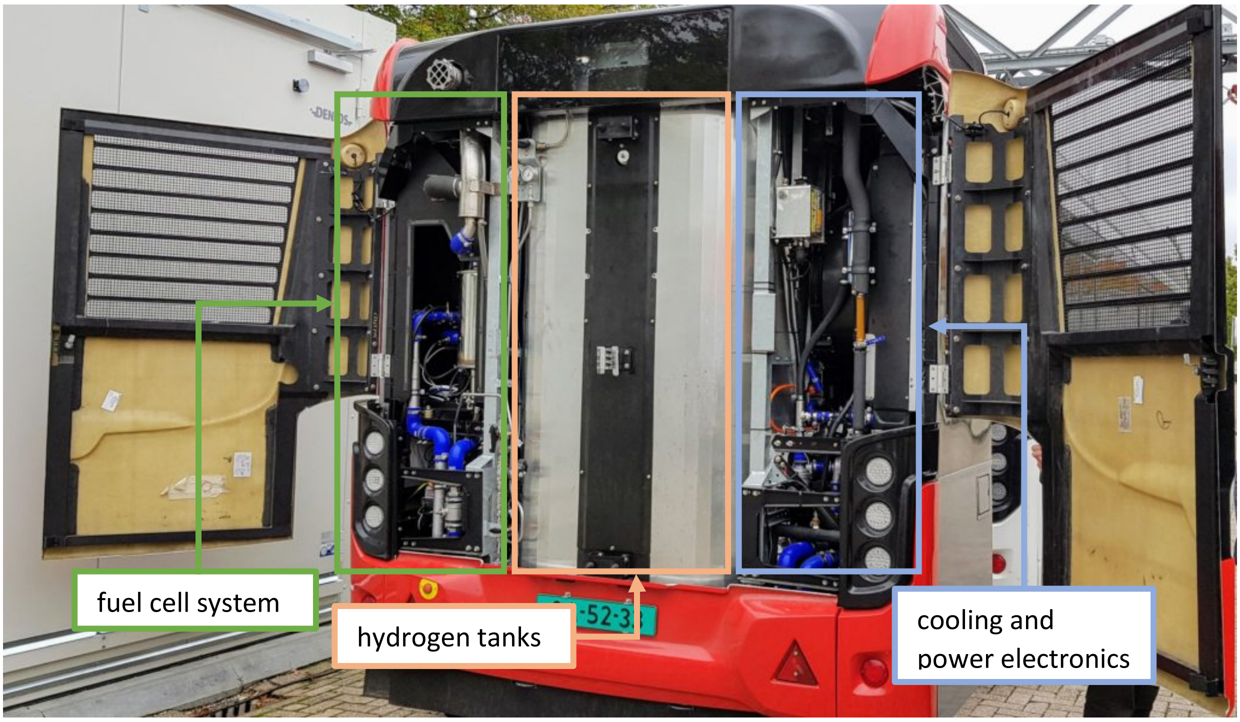

Fig. 11: GiantLeap fuel cell system (4)

The trailer itself is a VDL standard product and gets used for other applications as well. Radiator and fan are sufficient for providing a coolant temperature lower than 60°C at 40°C ambient temperature and a heat load of more than 70 kW power. Four 350 bar type 4 tanks hold a usable amount of about 30 kg hydrogen gas. Lighting and spring-loaded brakes receive their energy from the buses 24 V and pressurized air systems respectively.

3.2 Communication

Communication between the vehicle and the range extender system is provided by a CAN connection, based on CAN 2.0a protocol. While the vehicle controller generates the power demand, the FC controller feeds back the currently available system power output, depending on, amongst other variables, coolant temperature or environmental conditions. Table 1 lists the relevant signals sent on CAN between FC and vehicle controllers.

Signal origin	Signal	Relevant range
Vehicle controller	Fuel cell system power on	0 – 1
Vehicle controller	Fuel cell system emergency shut off request	0 – 1
Vehicle controller	Fuel cell system power request	0 – 80 kW
Vehicle controller	Vehicle main battery state of charge	0 – 100%
Vehicle controller	Voltage vehicle powertrain high voltage system	0 – 800 V
Vehicle controller	Vehicle speed	0 – 125 km/h
Vehicle controller	Vehicle mileage	0 – 1,000,000 km
Vehicle controller	State of vehicle high voltage contactors	0 – 1
Vehicle controller	H_2 tanks pressure	0 – 400 bar
Vehicle controller	H_2 tanks temperature	-40 – 200 °C
Vehicle controller	H_2 concentration tank compartment	0 – 4%
Fuel cell controller	Fuel cell stack output voltage	0 – 450 V
Fuel cell controller	Fuel cell stack output current	0 – 400 A
Fuel cell controller	Fuel cell system (DC/DC) output voltage	0 – 800 V
Fuel cell controller	Fuel cell system (DC/DC) output current	0 – 250 A
Fuel cell controller	Fuel cell state	0 – 8
Fuel cell controller	Fuel cell stack temperature	-40 – 100 °C
Fuel cell controller	Fuel cell system coolant temperature	-40 – 100 °C
Fuel cell controller	H_2 concentration stack housing	0 – 4%
Fuel cell controller	State of fuel cell system emergency shut down	0 – 1

Table 1: CAN communication between vehicle and fuel cell system

Noteworthy is the fact that, while all components in the trailer connected to the fuel cell system are also controlled by the FCCU, the hydrogen tanks are part of the vehicle control system. This is based on the trailer module also being used for other applications and could be room for improvement on future projects.

3.3 Commissioning

3.3.1 First firing at BEG premises

End of March 2019, the fuel cell system was completely built up in its framework, yet without axle and body parts. BEG engineers completed the wiring and made sure that all sensors and actuators were working. At the BEG premises in Abstatt, Germany, a hydrogen leakage test of the system was performed, external measurement devices applied, a data recording device installed and pre-configured (see also 4. Measurement Data Acquisition).

After the relevant calibration data had been taken over from the last test-bench data set, a short start-up test with 7kW output power could be performed for about 3 minutes. Due to limitations of the available laboratory equipment, longer lasting tests with higher load had to wait for the system to be fully connected to the vehicle.

The graph in Fig. 12 shows some data collected during first firing of the trailer system at BEG. The fuel cell provided about 7 kW, 20 A at 350 V, to an electric load and the controller passed all necessary control states.

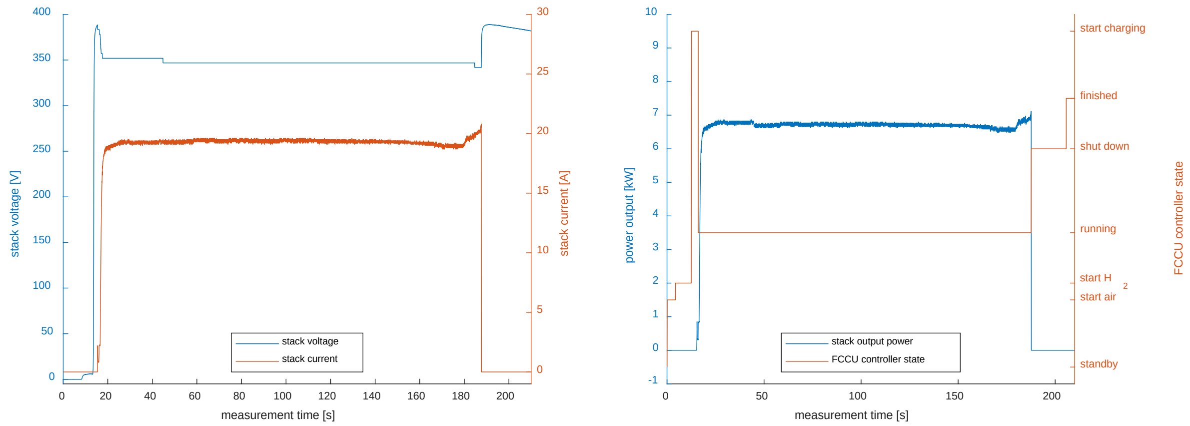

Fig. 12: First firing trailer system

3.3.2 Commissioning and Final Calibration

After completing the activities in Abstatt, BEG had the frame shipped back to VDL ETS to finish the build and connecting the trailer to the test vehicle. VDL ETS managed to finalize their tasks by end of June, so that in July the commissioning and final calibration of the completed range extender module could start. Unfortunately, a couple of minor faults, software bugs and failure of components continuously delayed the work, so that no un-interrupted testing phase could take place before the official end of the project in October 2019. Even though this was to be expected for a development and prototype build of such complexity, and even though throughout the project a lot of data and knowledge could be acquired, all parties involved would have liked to see a longer period of endurance testing. Fig. 13 visualizes the timeline of the commissioning at the VDL premises.

Fig. 13: Commissioning time line

The main task for the first week of vehicle commissioning in CW 27/2019 was the examination of all the differences between the test bench and the vehicle. Even after thorough preparation, the communication with the vehicle controller presented issues that had to be solved, calling for software updates in both, vehicle and FC controllers. For the calibration of the cooling system, no preparation could happen beforehand. Since the test bench delivered the cooling water in the laboratory, the vehicle calibration had to be done from scratch.

During calibration, it turned out that the hydrogen supply pressure was still set to a value too low for the GiantLeap FC system. Due to component lead times, the demonstration started in CW 34/2019 with a power limit of 40 kW to ensure sufficient hydrogen supply. Before, various third party components had failed and needed replacement. For more information about component failure, refer to chapter 6.2 of this report. Fig. 14 shows exemplary measurement data recorded during that phase. Controlled by the FCCU, the system output power matches the power demand of the vehicle controller up to the defined stack power limit. A slight variation in the stack voltage is mainly caused by the limitations of the cooling system and matches the fluctuation of the coolant temperature. Details concerning the cooling system will be covered in chapter 6.1.5.

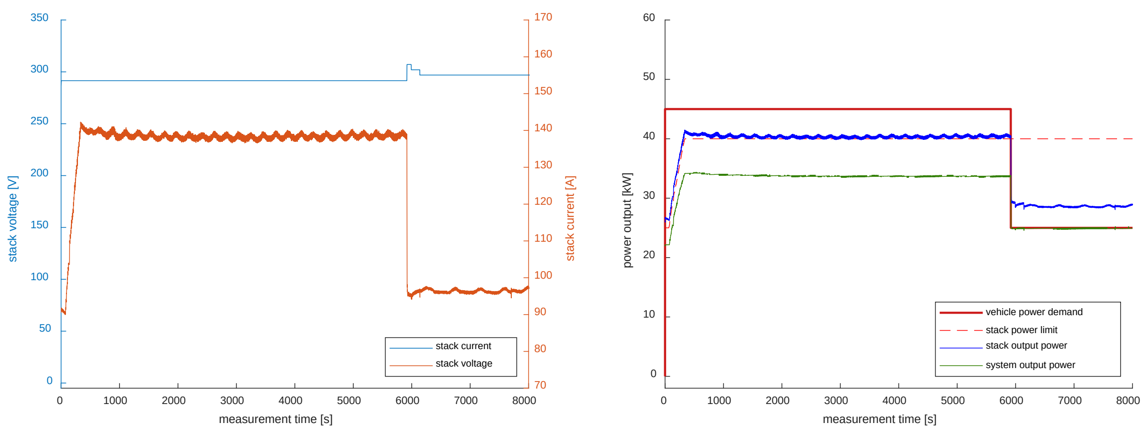

Fig. 14: Demonstration phase - example measurement

The hydrogen supply pressure could be raised in CW 38/2019 and a then changed calibration ensured a power limit of now 60 kW. The system could now run under full control of the vehicle power demand, until broken voltage and current sensor kept it from starting. A replacement sensor fixed this issue in CW 44, so VDL could run a couple more tests and shoot some video clips for promotion that will be available on the GiantLeap website (5). Since the project has officially ended by October 31, further developments will not be reported under the scope of GiantLeap.

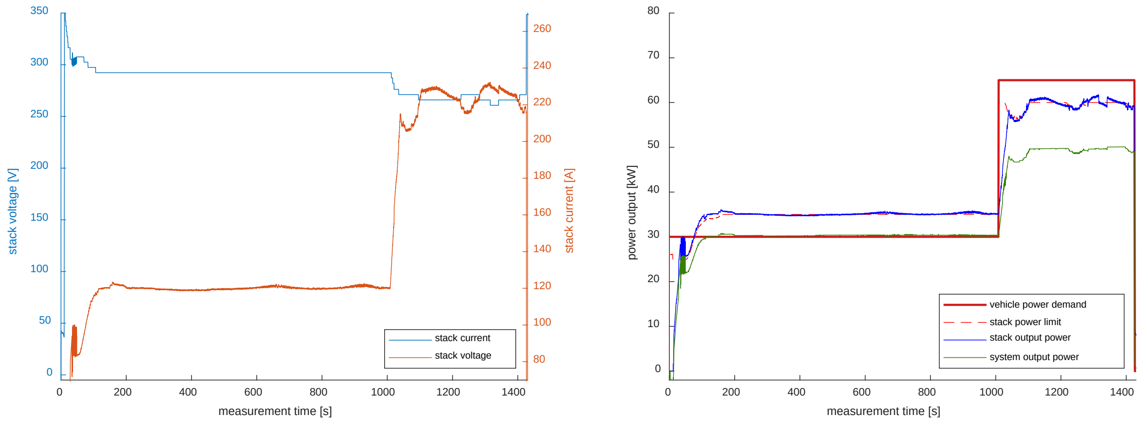

Fig. 15: Example measurement data of trailer system in use

4 Measurement Data Acquisition

4.1 ETAS ES820 Drive Recorder

Compliant to automotive ASAM standard, Bosch subsidiary ETAS GmbH, amongst other business, develops and sells hardware and software solutions for data acquisition and ECU calibration. For the testing phase, the range extender trailer was equipped with an ETAS ES820 drive recorder module.

Fig. 16: ETAS ES820.1 drive recorder module (6)

This device connects to any available ECU, CAN, or external sensor hardware. Via an embedded Windows 7 operation system, a pre-defined set of measurement data is recorded and made available via wired connection to a PC, WLAN, Flash Drive, or LTE mobile connection.

The ES820 module must be configured using a PC and ETAS INCA software and will then operate fully automatically.

4.2 Set-Up of Measuring Equipment

The ES820 drive recorder was set up to automatically start and record all relevant data from the fuel cell system and the connected vehicle. The embedded computer and Windows 7 operating system boots self-controlled as soon as the vehicle's main power is switch on. The recording then is started as soon as the FCCU controller receives a power demand on CAN from the vehicle controller.

For that reason, the ES820 module connects to the vehicle's terminal 15 signal, vehicle controller CAN, fuel cell system CAN, FCCU controller internal RAM memory, and some additional scientific sensors added to the system for further evaluation.

Through an internet connection established by an additional LTE surf stick, the acquired data is transferred to an ETAS administered SFTP server and from there downloaded to a BEG server drive. After some processing, all relevant data is then saved in CSV file format and made available to the project partners on a SINTEF owned server share. Fig. 17 shows a schematic overview of the data recording in the test vehicle.

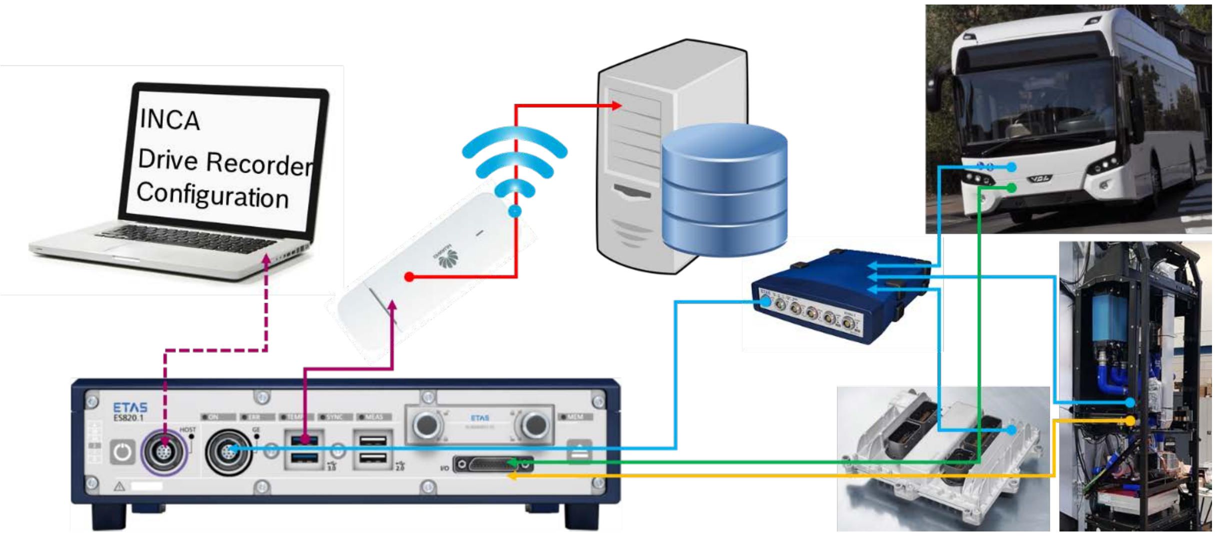

Fig. 17: Set-up or data recording devices in the test vehicle

4.3 Data Measured

At the beginning of GiantLeap project, the project partners agreed on a list of relevant measurement data that was recorded in various ways throughout the operation phases of the system.

Table 2 lists all data labels, which GiantLeap will also make available to the public within WP7.8.

Subsystem	Acronym	Physical Unit	Description of Parameter
Air system	AirMassFlow_dm	kg/h	Current air mass flow
	AirMassFlowDes_dm	kg/h	Desired air mass flow
	AirComprDes_rat	%	Desired air compressor actuation ratio
	AirCompr_rat	%	Current air compressor actuation ratio
	AirCompr_n	rpm	Current air compressor drive speed
	AirSt1Out_pAbs	hPa (abs)	Air pressure outlet (stack 1)
	AirSt2Out_pAbs	hPa (abs)	Air pressure outlet (stack 2)
	AirSt1Out_T	°C	Air temperature outlet (stack 1)
	AirSt2Out_T	°C	Air temperature outlet (stack 2)
	Env_T	°C	Environment temperature
	Env_pAbs	hPa (abs)	Environment pressure
	AirBypVlv_rat	%	Bypass valve ratio
	PresRegVlv_rat	%	Throttle valve ratio
H2 system	H2Tank_p	hPa (abs)	Current H2 tank pressure
	H2Tank_T	°C	Current H2 tank temperature
	H2TankVlv_rat	%	High pressure tank valve ratio
	H2MedPVlv_rat	%	Medium pressure valve ratio
	H2MedPVlv_rat	%	Medium pressure valve ratio
	H2St1In_pAbs	hPa (abs)	Current H2 inlet pressure (stack 1)
	H2St2In_pAbs	hPa (abs)	Current H2 inlet pressure (stack 2)
	H2StInDes_pAbs	hPa (abs)	Desired H2 inlet pressure
	H2St1Out_pAbs	hPa (abs)	H2 outlet pressure (stack 1)
	H2St2Out_pAbs	hPa (abs)	H2 outlet pressure (stack 2)
	H2Anod1_pDiff	hPa	Differential pressure at anode loop stack 1
	H2Anod2_pDiff	hPa	Differential pressure at anode loop stack 2

Subsystem	Acronym	Physical Unit	Description of Parameter
	H2RegVlv1_rat	%	Desired hydrogen pressure regulator valve ratio stack 1
	H2RegVlv2_rat	%	Desired hydrogen pressure regulator valve ratio stack 2
	DrainVlv_rat	%	Drain valve ratio
	PurgVlv_rat	%	Purge valve ratio
Cooling system	CooltStIn_p	hPa (abs)	Cooling pressure inlet
	CooltStIn_T	°C	Cooling temperature inlet stack 1
	CooltSt1Out_T	°C	Coolant temperature outlet stack 1
	CooltSt2Out_T	°C	Coolant temperature outlet stack 2
	CoolFan_rat	%	Fan ratio
	CoolFanEE_rat	%	Fan ratio E/E system
	CooltPmp_rat	%	Cooling pump ratio
	AuxCPmp_rat	%	Cooling pump ratio E/E system
	CooltVlv_rat	%	2/3-way-valve ratio
Electrical system	Term15_st	-	Terminal 15 signal (vehicle ignition switch)
	BatLV_U	mV	LV battery voltage
	FCCtrl_st	-	Status of the fuel cell system
	Stack_I	A	Current stack current
	Stack_U	V	Current stack voltage (filtered value)
	Stack_Pwr	kW	Stack power setpoint
	StackAvg_R	mOhm	Average stack resistance (averaged over 1 min)
	StackAvg_R	mOhm	Average stack resistance (averaged over 1 hour)
	StackAvg_I	A	Average stack current (averaged over 1 min)
	StackAvg_I	A	Average stack current (averaged over 1 hour)
	ELFIS_R	Ohm	ELFIS calculated resistance
	ELFIS_U	V	ELFIS calculated tension

Subsystem	Acronym	Physical Unit	Description of Parameter
Vehicle	VehFCDes_Pwr	kW	Power Demand issued by vehicle controller
Safety	BlowrStHousg_dm	kg/h	Mitigation air mass flow
	BlowrStHousg_rat	%	Current mitigation fan ratio
	H2ConcHousg_rat	%	H2 concentration stack housing
	H2ConcExh_rat	%	H2 concentration at exhaust pipe

Table 2: Data recorded during testing

5 Operation Strategy

During commissioning, especially on the test bench, BEG engineers in co-operation with ElringKlinger's stack specialists, characterized the power range feasible for stable operation. The FC system is designed to operate at a minimum power of 20 kW, limited by calibration of the relevant FCCU parameters. The use as range extender module in combination with a rather large battery capacity of the bus creates no demand for a lower idle power. Maximum available net output power of the system, as proven on the test bench, would be about 70 kW. Nevertheless, due to the challenges faced with the cooling system, for the REx trailer the maximum was limited to 60 kW and will be further reduced automatically depending on the coolant temperature.

Depending on different parameters, amongst others the main battery's state of charge, the vehicle controller calculates a power demand for the fuel cell system as CAN message. Depending on the current state of the fuel cell system and environmental conditions, the FCCU calculates power, current, voltage, available at any given moment and feeds that value back, again in a CAN message. Fig. 18 gives an overview of the most important signals on CAN.

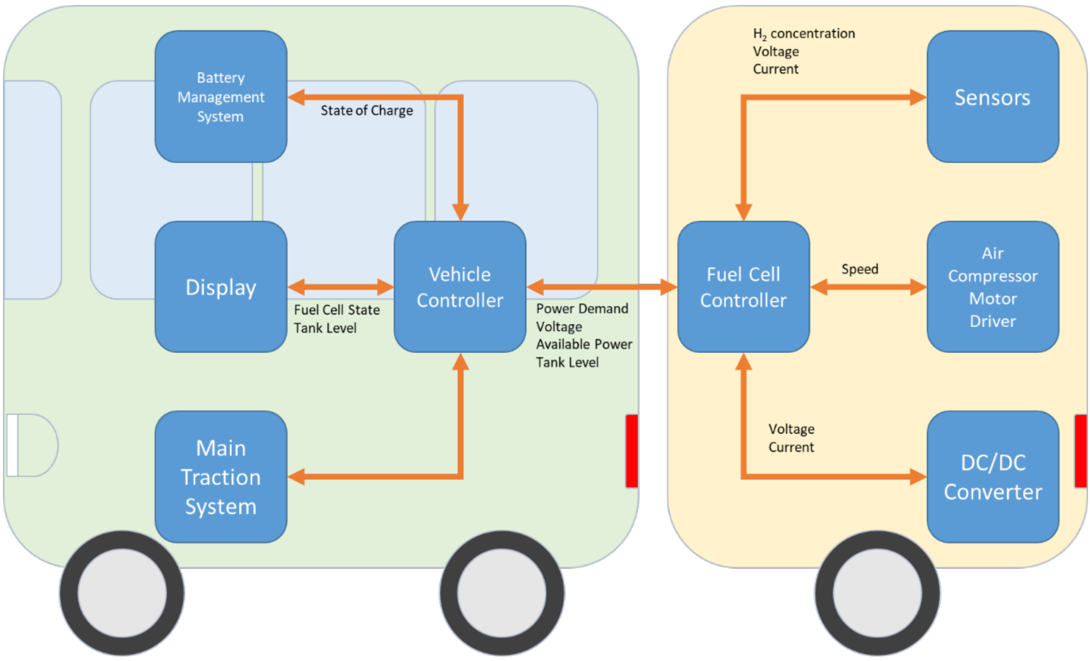

Fig. 18: CAN communication overview

6 Test results

6.1 Overall Performance

6.1.1 System

With two fuel cell stacks rated at a maximum power of 40 kW each, a maximum system net output power of 72 kW could be achieved on the system test bench. In the vehicle, the maximum power was limited to 60 kW on stack level to improve efficiency and durability.

On the test bench, the system was tested and operated in various conditions for a total of about 700 hours. In addition, the system built into the range extender trailer accumulated approximately 100 hours of operation.

The next paragraphs give an overview of the performance on sub-system level. Even though commissioning, calibration and testing got repeatedly halted by relatively minor issues, no major components failed during the course of the project. The overall performance of the system exceeded the expectations.

6.1.2 Fuel Cell Stacks

The ElringKlinger NM-5 FC stacks used in GiantLeap showed great performance throughout the project. During commissioning and calibration a quite significant number of events happened, that could possibly have caused the stacks to fail. Events like fuel starvation, over pressure, cells operated under conditions too wet, too dry, too hot, emergency shut downs of the system or the test environment, right down to human error, happened and have to be expected in a laboratory environment. Still, right to the end of the project, the stacks were in their specified power range.

6.1.3 Sub-System Air

For many fuel cell systems, the air compressor is known as a major source of trouble. Because of the traction oil, the Rotrex compressor used in the GiantLeap system was not the first choice but at that time the only component readily available. Nevertheless, aside from one failure during component testing due to an operation point outside of the specifications as reported in D5.3 (7), the compressor did not cause any problems and lasted for the whole project without any noticeable degradation or failure.

Likewise, the H50 hollow fiber membrane humidifier by Fumatech provided intake air sufficiently humid throughout the whole project. Even though the component testing revealed a performance loss of about 50% at relatively low humidity (7), no issues occurred on system level. Since the humidity of the membranes is essential for the performance of the fuel cell itself, further investigation seem appropriate.

The Bosch DV-E throttle valves used for backpressure and cathode bypass control have not been released for operation in fuel cell systems. Neither the materials used nor the sealing solutions are suited to keep the component protected from corrosion caused by de-ionized water. For the duration of the GiantLeap project, the valves did not cause any major issues concerning durability, a solution for series production demands further development. Caused by the principle of a butterfly valve, the blade used in the cathode bypass tended to get stuck in closed position. Calibration provided a solution by accepting a slight internal air leakage between cathode intake and exhaust but leaves room for improvement in further development.

To prevent oxygen penetration into the cathode during standstill after bleed down of the system, spring loaded isolation valves shut the air path on both sides of the stacks. Those were prototype parts developed by BEG based on an existing design. Even though the design was not completely ideal for the task, the valves worked throughout the project without attracting any attention.

6.1.4 Sub-System Hydrogen

The hydrogen supply system was provided by VDL as part of their standard fuel cell trailer module. The tanks itself did not present any issues. Because of the trailer being used for other fuel cell systems as well, the standard settings and components for the medium pressure of nine bar had not been changed. Adjusting the pressure to the desired 15 bar lead to a failure of the adapted pressure relieve device and hence a hydrogen leakage to the environment.

Even with a supply pressure of only nine bar, the hydrogen low-pressure regulation valve HGI by Bosch together with an ejector pump designed by ElringKlinger to ensure anode recirculation worked well and made for a reliant and stable anode recirculation.

During commissioning, BEG calibration engineers observed temporarily high hydrogen concentration in the exhaust gas in connection with the anode purge. After changing both purge valves, no further issues occurred.

6.1.5 Sub-System Cooling

By far the most issues occurred with the cooling system. During the project, it became apparent that the effort invested into the design was insufficient, so that controlling a stable stack intake temperature was effectively not possible. The original design provides for a temperature control via fan speed with a radiator bypass including an electrical heater for warm-up only. With a powerful radiator-fan-combination provided by the trailer module and a large volume of coolant, the heat losses at low ambient temperatures however, make it necessary to have a controlled inner coolant circle capable of full flow.

The only electronically controlled coolant bypass valve apparently available on the market by Buschjost causes a rather significant pressure loss, so that maintaining a sufficient coolant flow becomes difficult with available automotive grade pumps. Beyond that, near the end of the project a component within the control chain of that coolant valve failed, so that it could no longer be moved. To enable further use of the REx, BEG adapted the calibration so that an operation was possible with a variance of the coolant intake temperature of about 15°C peak to peak.

The lessons learned include the need for more powerful coolant pumps, preferably with HV drive, and the realization that an inner coolant circuit, controlled by a passive thermostat valve will probably provide sufficient accuracy.

Throughout the project, there were no issues with the coolant itself, conductivity being constantly monitored in the test bench system and regularly checked in the trailer.

A second, independent cooling system for the HV electronic components required some calibration work to reduce the noise produced by the fan. Other than that, it worked without any abnormalities.

6.1.6 Sub-System Electrics and Electronics

The compressor motor Bosch SMG138 and corresponding inverter Bosch InvCon 2.3 are standard parts and only needed some adaption to provide stable operation during the whole project. Due to faulty calibration values, the power provided by the 12 V DC/DC converter part of the InvCon 2.3 was not sufficient at the beginning of the trailer commissioning. This caused the 12 V battery to fail.

To convert the voltage provided by the fuel cell system to the level needed by the vehicle HV-bus, the design includes a DC/DC converter in A-sample state. One of the parts BEG used during the project failed and had to be replaced. In the trailer, it worked as intended while minor inaccuracies in the control commands via CAN caused a shut-down of first the DC/DC converter and in consequence the whole FC system. Further work will be necessary.

As a part of the trailer module and permanently supplied by the vehicles 700 V electrical system, the mail cooling fan only received control signals from the FCCU controller. Based on a commercial vehicle 24V development, the Fan controller caused issued with the low voltage level dropping too low. For the GiantLeap prototype it was possible to adapt the calibration for a working configuration, so no further problems occurred.

Main source of the controller feedback for the power regulation are voltage and current signals measured by a shunt current sensor. One of those sensors broke near the end of the project and had to be replaced. A first visual inspection did show cracks and a deformation of the housing pointing to excessive heat (Fig. 19: Broken current sensor). Investigation into the cause of the failure is still ongoing.

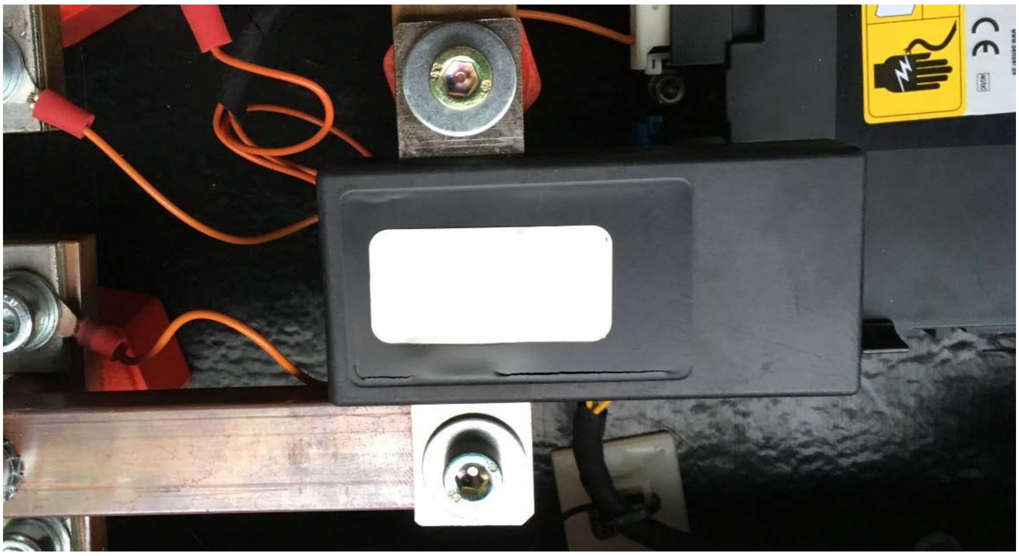

Fig. 19: Broken current sensor

Single cell voltage monitoring is a good means to keep track about the state of the fuel cell stack. In the case of GiantLeap, the lowest cell voltage is used in the FCCU to trigger various reactions, in the worst case to shut down the system. During the course of the project, BEG alone three different CVMU systems. None of them proved reliable enough to not cause problems with broken connections, faulty measurements, or unreliable CAN communication to only name some. The unit used on the vehicle system did intermittently transmit ‘0 V valid’ on the lowest cell voltage signal for the duration of one or two CAN message frames, causing the system to shut down. This issue could be solved by filtering the input signals and de-bouncing the error reaction in the FCCU software, but it proves, that single cell voltage monitoring is great laboratory equipment but at least as of today is not mature enough for use in production vehicles.

For easy access to the controller software during software development and calibration, automotive engineers often use control unit hardware with additional controller and RAM chips attached. An appropriate interface connected to a laptop computer then allows for monitoring of internal bus data traffic or online changes of parameters. Fig. 20 gives an overview of the ETAS ETK-T2.2 used in GiantLeap. These control units are commonly used in prototype vehicles and systems but can from time to time cause trouble, since obviously the durability does not match automotive lifecycle demands. The FCCU used in the trailer caused hardware resets and had to be changed.

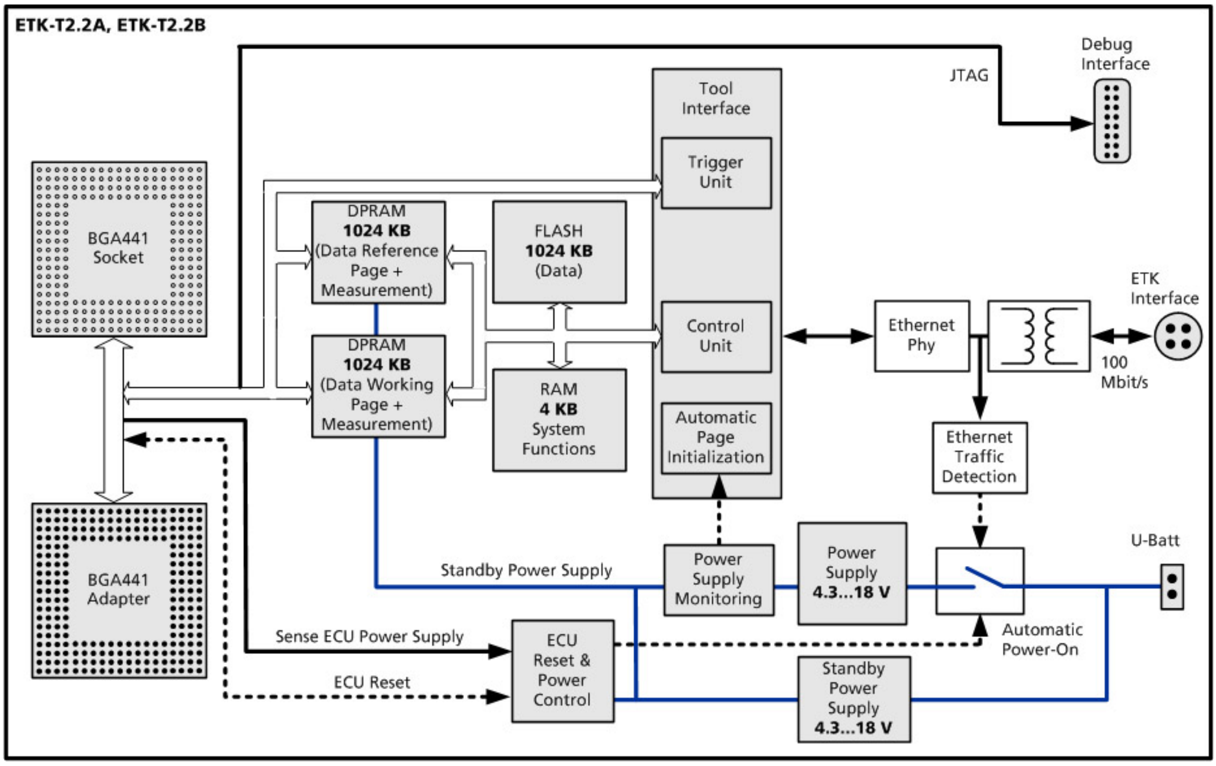

Fig. 20: Schematic of ETAS ETK-T2.2 calibration hardware (8)

6.2 Failure of components

Throughout the project, the main components hardly caused any issues. The only key component failing was one of the DC/DC converter A-samples and components actively destroyed by miss-use during component testing. Main source of trouble were small and relatively cheap third party components. Table 3 provides an overview of components that caused issues.

Component	Description of failure	Solution
DC/DC converter	Defective output stage	Repair by manufacturer
Cathode bypass valve	Tends to get stuck when closed to mechanical stop	Close only to electrical stop
CVM unit	Minimum cell voltage is sporadically sent as valid 0V on CAN	Filter values in controller software
FCCU ETK-T2.2	Unwanted hardware resets	Change FCCU hardware
H_2 CAN sensor	H_2 concentration signal on CAN valid 12.7% (0xFF) for very long time during start up	Debounce long enough in FCCU software

Component	Description of failure	Solution
Purge valves	Anomaly in purge function, high H_2 concentration in exhaust gas	Replace valves
Main cooling fan	24 V variant PWM signal 15…28 VDC required	Raise LV voltage level to 14.5 V
12 V battery	Battery exhausted, 12 V power supply not sufficient	Battery replaced, calibration corrected, data recording needs to be switched off during longer stand-still
Coolant control valve	Control device half bridge circuit defective	Valve set to 60% and fixed, work-around by calibration
Pressure relief device hydrogen mid pressure	Blow-off causing H_2 leakage	H_2 mid pressure reduced (16.4 bar_a → 15.8 bar_a)
Current sensor	Defective, sensor switching off during operation	Sensor changed, investigation ongoing
Drive recorder	Defective, device not booting	Drive recorder changed, investigation ongoing

Table 3: Failure of components

One more factor not directly connected to the development of the fuel cell system was defects of the vehicle connected to the trailer. Calibration and testing could in a wide range be done in standstill. Nevertheless, for fill the hydrogen tanks and draining the main traction batteries the vehicle had to move. Since the electric drivetrain also had prototype status, failure of components driving cooling water pumps or air brake compressors at multiple times stalled the work on the FC REx trailer.

7 Conclusion and Prospects

Under the scope of GiantLeap, the project partners developed a FC REx system basically from scratch, that could operate without supervision on public roads controlled by an automotive grade control structure. A lot of knowledge concerning design, operation, durability, and diagnostics of an automotive fuel cell system could be gained.

Two complete prototype systems were built during the project, the first to be run on the test bench, a second for the REx trailer. For comparison, in a standard development project for combustion engines, a minimum of two or three engines would be calculated to crash during test bench calibration only. Even for low volume high performance engines, a manufacturer would produce a minimum of five prototypes for engine calibration.

Taken into consideration the resources and budget available, a lot has been achieved in GiantLeap project. VDL ETS together with ElringKlinger will continue working together on fuel cell systems for use commercial vehicles in upcoming projects, like H2Haul, which like GiantLeap is also founded by FCH-JU (9). Insights and knowledge gathered in this project will definitely fuel further development. Due to various decisions made within the Robert Bosch Group, BEG will currently not be able to co-operate with ElringKlinger and VDL ETS on further developments based on the GiantLeap system. Nevertheless, as is publicly known, the Robert Bosch Group is highly invested in bringing fuel cell technology forward. The knowledge gained in GiantLeap project has been, and still is, a major contribution to the decisions made in that context.

8 Figure and Table Overview

9 Table of Abbreviations

AC	Alternating current
BEG	Bosch Engineering GmbH
CAN	Controller area network
CSV	Comma separated value
CVMU	Single cell voltage monitoring unit
CW	Calendar week
DC	Direct current
DC/DC	Direct current to direct current voltage converter
ECU	Electronic control unit
E/E	Electric and Electronic
EK	ElringKlinger AG
ETAS	ETAS GmbH, Stuttgart
ETK	Software development hardware added to an ECU (Emulator Tastkopf)
FC	Fuel Cell
FCCU	Fuel Cell Control Unit
HGI	Hydrogen gas injector valve
HV	High voltage
INCA	Integrated measuring and calibration software (ETAS product)
InvCon	Integrated Inverter and Converter
LTE	Long term evolution (4th generation mobile communications standard)
LV	Low voltage (< 60 VDC, < 30 VAC)
PC	Personal computer
PEM	Proton exchange membrane
PWM	Pulse with modulated
QA	Quality assurance
RAM	Random access memory
REx	Range Extender
SINTEF	Foundation for industrial and technical research (Stiftelsen for industriell og teknisk forskning)
SMG	Separate motor and generator
VAC	Volts alternating current
VDC	Volts direct current
VDL ETS	VDL Enabling Transport Solutions b.v.
WP	Work Package

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