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Department of the Environment,
Transport, Energy and Communication DETEC

Swiss Federal Office of Energy SFOE
Energy Research

Final report

Hydrogen fuel cell range extender for Renault Kangoo ZE

Integration and testing

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SFOE contract number:	SI/500905-01

Summary

The goal of this project is to integrate a 10kW Fuel Cell range extender into an electric Renault Kangoo ZE to double at least its usable energy with the hydrogen storage and the fuel cell systems. Initial calculation shows that additional useable 25 kWh can be added. The Kangoo ZE has been equipped with the hydrogen range extender and homologated for Swiss roads. The Kangoo has been chosen because it's one of the most appreciated utility vehicle in Europe and has already a proven Electric version available in series and on the market since 2012. The modified vehicle has been delivered to its final user in September 2017 and some preliminary performance analysis following 9 months of services are presented.

Résumé

L'objectif de ce projet est l'intégration d'un prolongateur d'autonomie sur une Renault Kangoo électrique sous la forme d'une pile à combustible de 10kW qui permet d'au moins doubler l'énergie utilisable, avec 25 kWh électrique stocké sous forme de dihydrogène compressé. La Kangoo ZE a été homologuée pour circuler sur les routes suisses. Cette voiture a été sélectionnée car c'est l'un des véhicules utilitaires les plus utilisés en Europe qui dispose d'une version électrique produite en série depuis 2012. Le véhicule modifié été livré au client final en Septembre 2017 et des analyses préliminaires de performances après 9 mois d'utilisation sont présentées.

Contents

List of abbreviations

CTP	Potential Temperature Control
CVM	Cell Voltage Monitor
DC	Direct Current
DTC	Dynamic Test Center
ECU	Electronic Control Unit
FCS	Fuel Cell System
H2	Hydrogen
HV	High Voltage
HSL	Hardware Safety Layer
LV	Low Voltage
SHSA	Swiss Hydrogen SA
SOC	State Of Charge

1 Introduction

The electric vehicle market is today growing rapidly mainly due to their reduced impact on the environment and the cost reduction of the Li-ion battery packs and electrical drive trains.

However battery systems present two major limitations which are their charging time and their relative important weight. Car makers are then facing a trade-off between limiting the drive range or the workload of their vehicle, compared to the fossil fuel solution.

In this context, hydrogen storage in high pressure composite tanks combined with a fuel cell system offers an efficient solution to extent the drive range with the possibility to recharge the tanks within a few minutes, while increasing the stored mass energy density by a factor 3.

2 Project description

The goal of this project is to equip an existing electric vehicle with a Swiss Hydrogen fuel cell range extender. Thanks to good relationship with the EVs department of the Renault Group, the vehicle retained was the Kangoo ZE (Fig 1).

Fig 1 : The Renault Kangoo ZE.

The Kangoo ZE has a basic range of 80km to 125km with his 22 kWh battery. The target was to double this usable energy with the hydrogen storage and the fuel cell systems.

The best solution was to place the fuel cell itself along with its aggregates under the hood in the front and place the hydrogen storage system under the vehicle between the rear wheels (Fig 2).

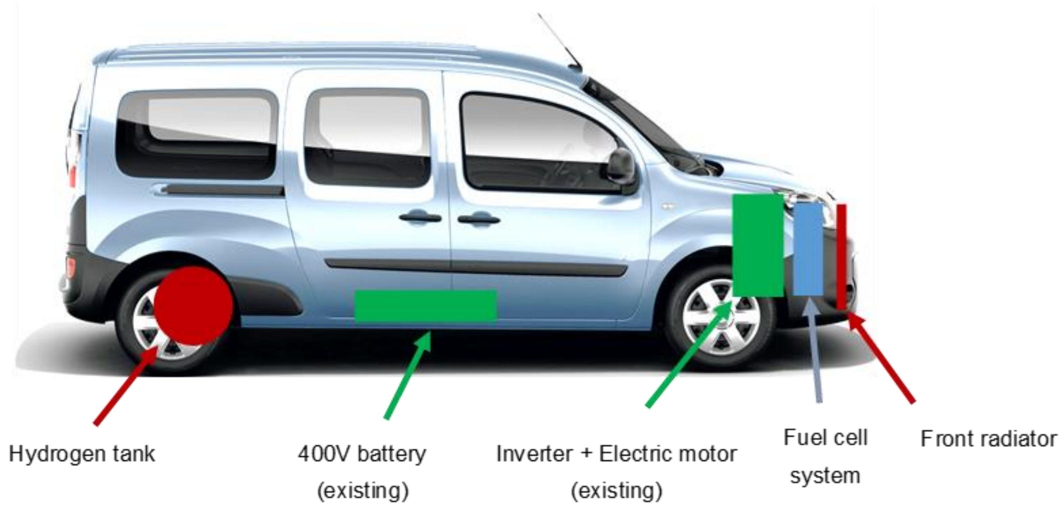


Fig 2 : Initial packaging study.

This project has been divided into work packages consisting of:

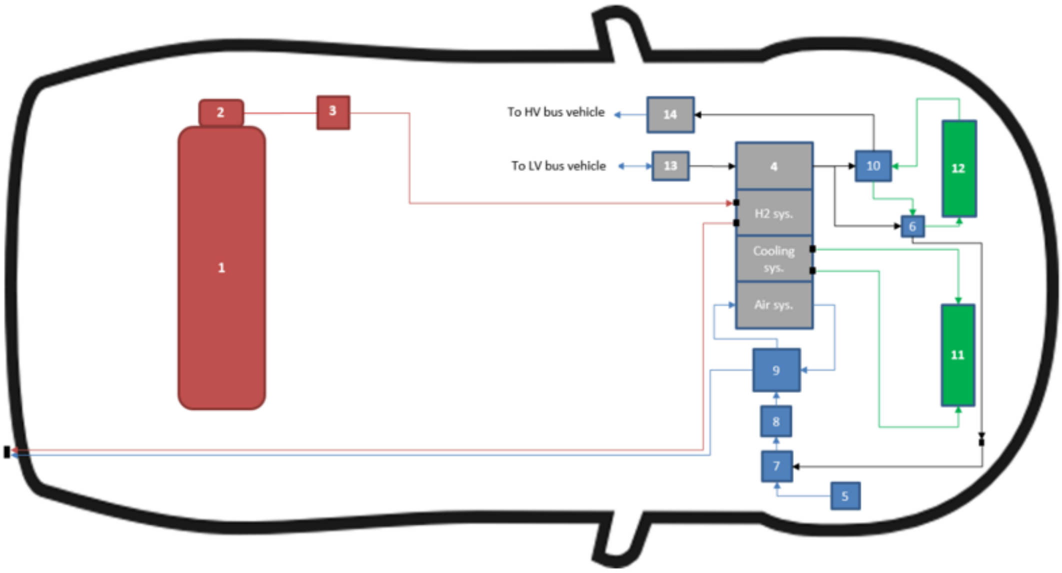
- WP1 Mechanical Integration
- WP2 Electrical Integration
- WP3 Calibration and Testing
- WP4 Homologation
- WP5 Real drives analysis

The technical specifications of the FCS are presented in table 1

Base vehicle		
Model	Renault Kangoo ZE	
Motor Power [kW]	44	
Battery energy [kWh]	22	
Range [km]	170 (NEDC)	80 – 125 (normal)
Range Extender		
Model	Swiss Hydrogen 10 kW fuel cell system	
Power [kW]	10	
H2 storage	40L - 700 bar type IV cylinders	
H2 mass stored [kg]	1.7	
RE energy available [kWh]	27	
Additional range [km]	210 (NEDC)	100 – 150 (normal)

Table 1 : Vehicle and range extender specifications.

A general overview of the integrated components in the electrical car is illustrated in figure 3:



1	H2 tank	8	Intercooler
2	H2 tank valve	9	Fuel cell humidifier
3	Pressure reducer	10	HV DCDC converter
4	Fuel cell system	11	Fuel cell cooling Radiator + Fan
5	Fuel cell air filter	12	Electronic cooling Radiator + Fan
6	Fuel cell compressor electronic	13	LV junction box
7	Fuel cell compressor	14	HV junction box

3

Fig 3 : Mechanical components to integrate

3 Technical achievements

3.1 Mechanical Integration

3.1.1 The hydrogen tanks

The tank that was selected for the project is the Luxfer 74L, 350 bar hydrogen cylinder. Due to its smaller diameter, a 700 bar cylinder would have been easier to integrate, but would have given less extended range when filled at 350 bar. Since the hydrogen station in Martigny (EPFL) only provides a fast fill on the 350 bar, it was decided to integrate the Luxfer 74L, 350 bar cylinder containing 1.7kg of hydrogen, thus providing 170km of extended range.

With the aim to keep the maximum loading volume in the vehicle, it was decided to place the hydrogen tank behind the back wheels. Due to its 415mm in diameter, we had to cut the floor of the vehicle in order to keep enough ground clearance, as shown in Fig. 4.

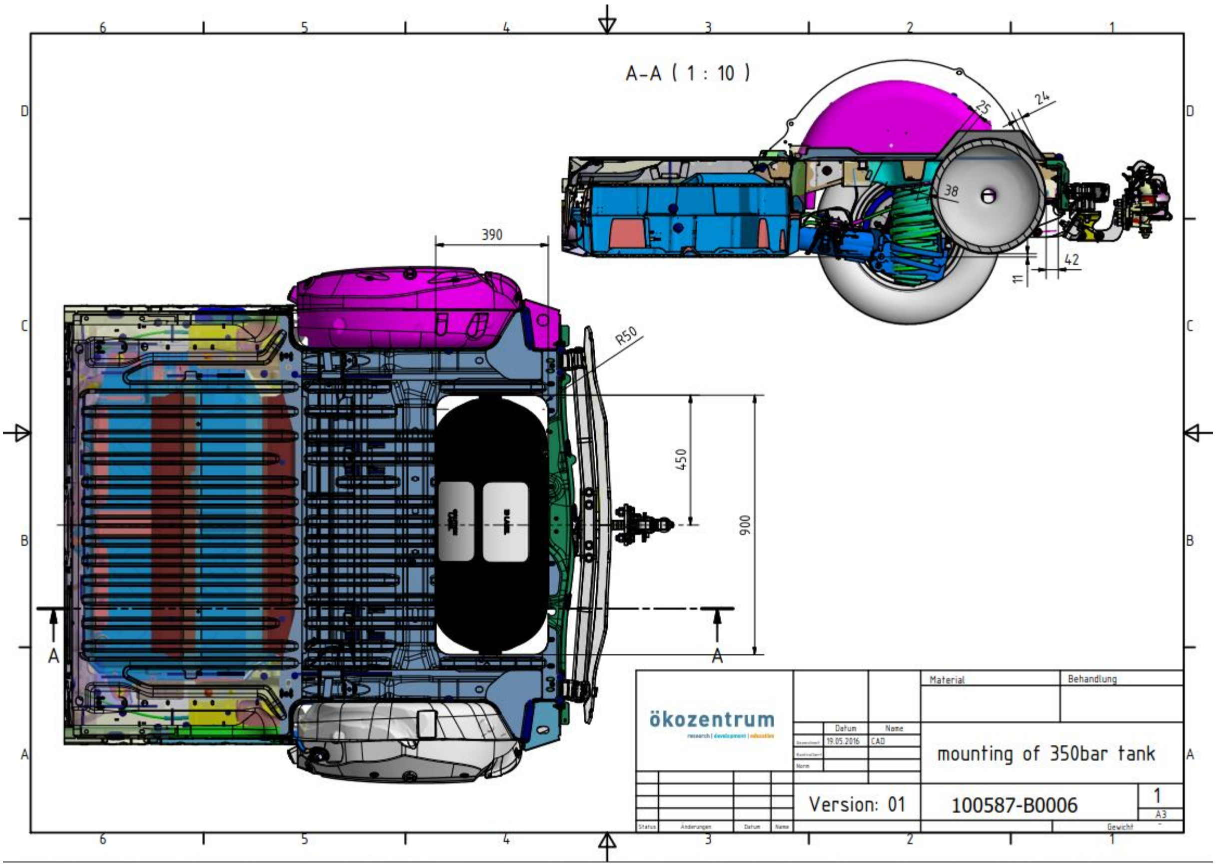


Fig 4 : Initial CAD of the 74L hydrogen tank integration.

After detailed construction design were made for the fixation of the hydrogen tank (see Fig. 5 and 6), FEM simulations have been carried out to control the robustness of the integration and its resistance in case of a crash (see Fig. 7). These simulation results were required to obtain a positive report from the Dynamic Test Center (DTC), which was a precondition for the homologation approval.

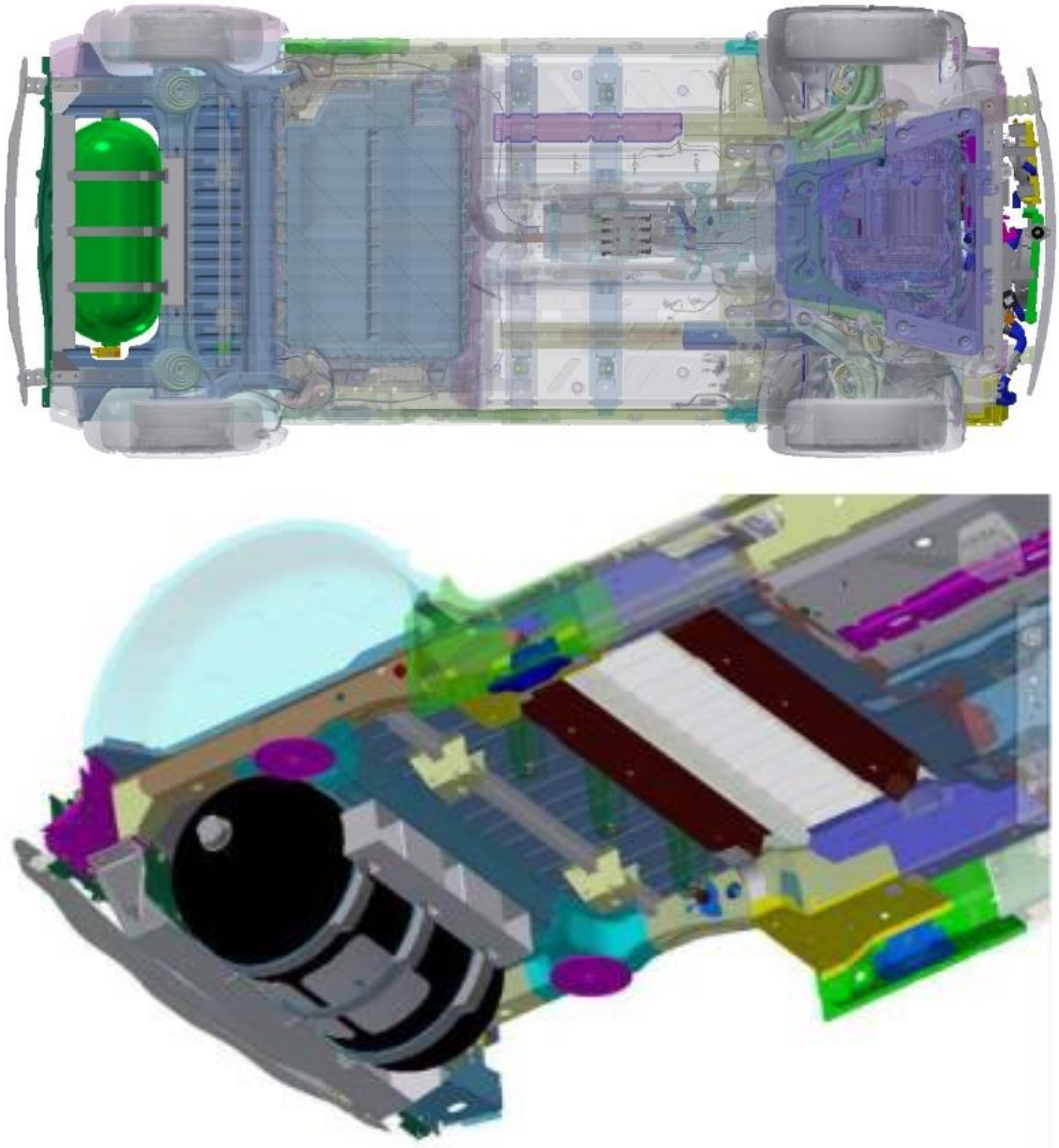


Fig 5 : Detailed CAD of the integration and fixation system of the hydrogen tank.

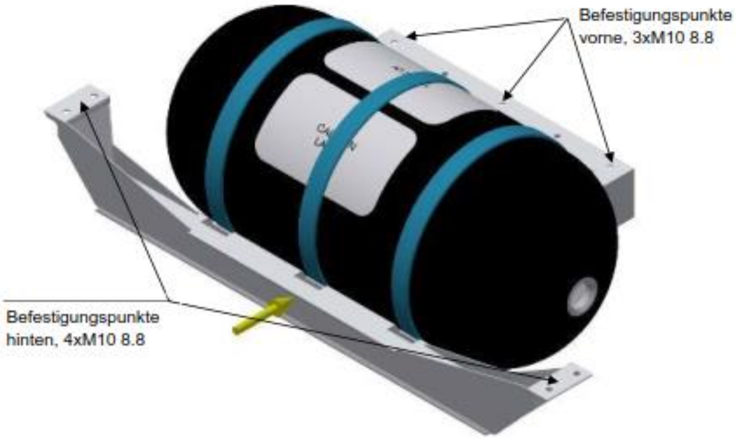


Fig 6 : Design of the fixation system used for the FEM simulation.

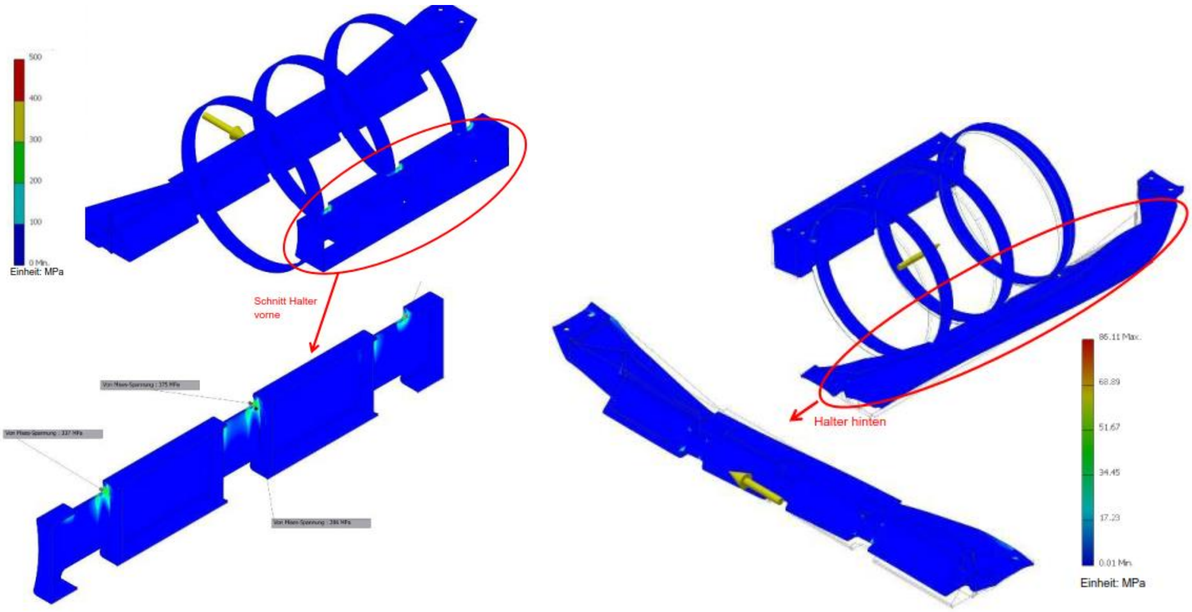


Fig 7: FEM simulation with 20g in forward direction (left) and 8g in side direction (right).

These FEM simulations showed that the construction would suffer little deformation in case of 20g impact in driving direction and 8g transversal impact.

After this verification, the hydrogen tank integration work could be started with the following adjustment on the car floor:

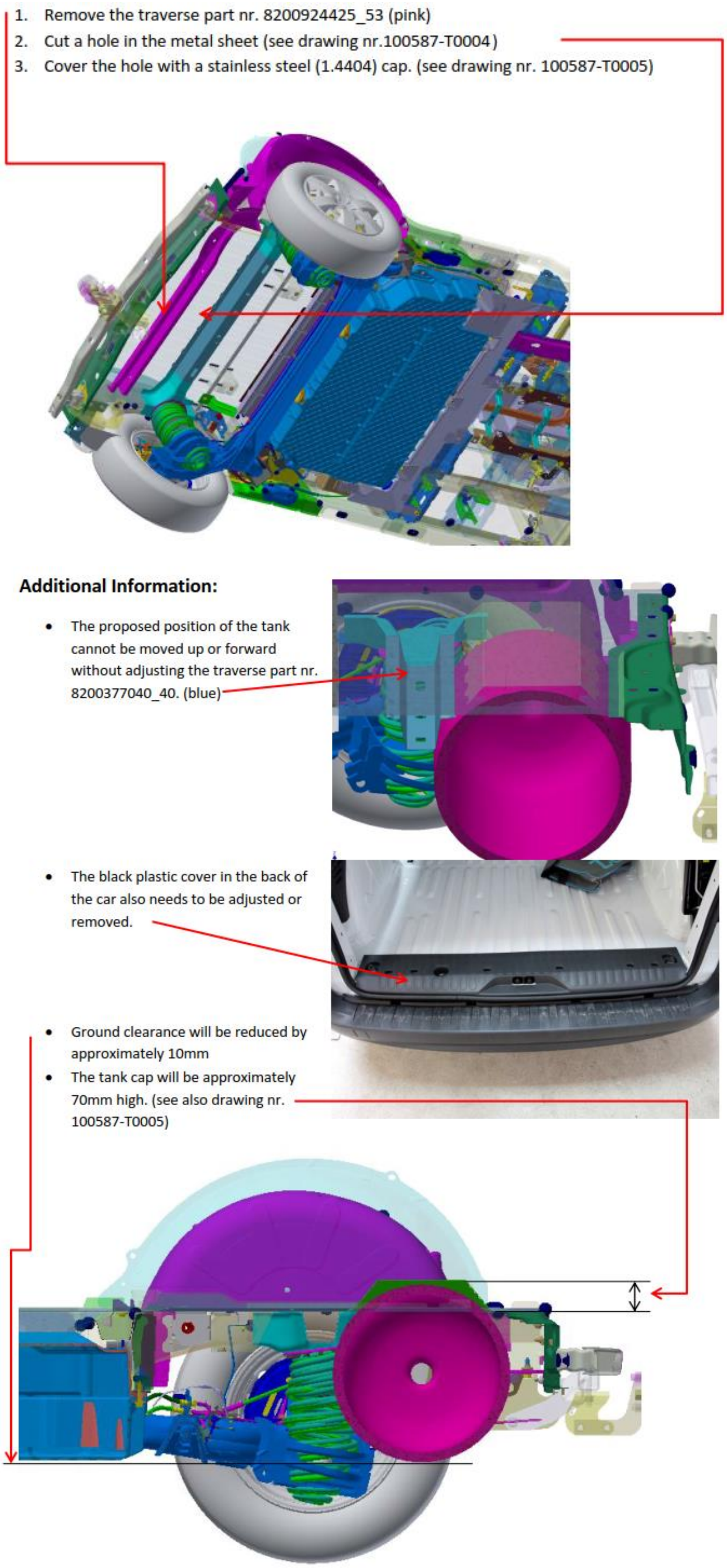


Fig 8: Adjustment description on the car floor for the H_2 tank integration

Since they are “carrossier agréé” by Renault to perform such transformation on the vehicles, the Carrosserie Warpel in Fribourg was chosen to do the cutting of the car floor.

After reception of all the parts, the hydrogen tank was mounted on the vehicle (see Fig. 9 and 10).

Fig 9 : Top view of the mounted hydrogen tank (main) and 350 bar WEH nozzle integrated in the fuel trap of the vehicle (insert)

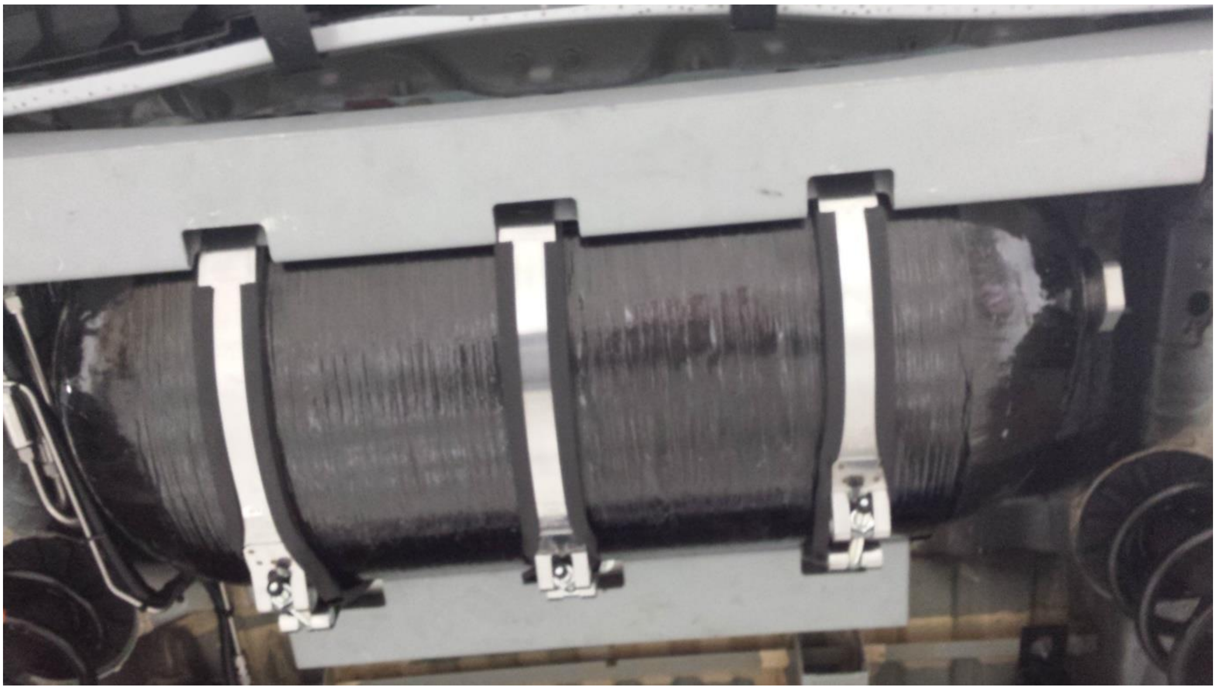


Fig 10 : Mounted hydrogen tank (bottom view)

For the 350 bar fast refueling, the standard WEH hydrogen nozzle was integrated in the fuel trap of the vehicle (see insert in Figure 9).

The high-pressure piping was then connected to the in-tank valve with the thermal pressure release device (TPRD) with an angle in the direction of the ground (Fig. 11 and 12).

Fig 11**:** High pressure piping (350 bar) with TPRD (orange encircled).

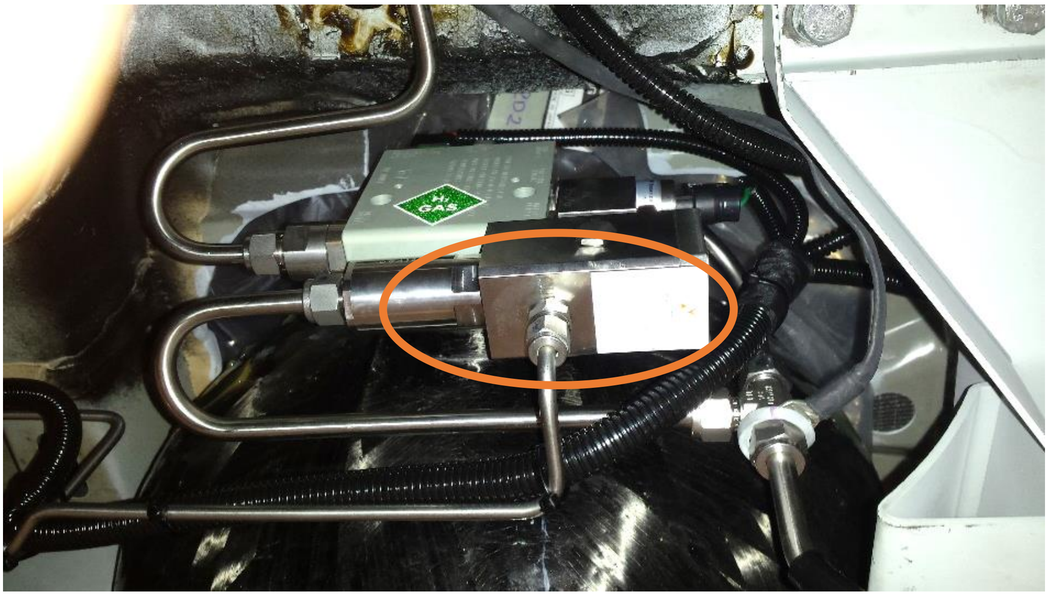


Fig 12: High pressure piping with in-tank valve and pressure reducer to 10 bar for fuel cell feeding (orange encircled).

3.1.2 The FCS

The fuel cell system itself was redesigned in order to integrate numerous improvements. The accumulated experience on the Fiat system has motivated additional redesign points that have been realized during this project:

1. Replaced Injector by proportional valve
2. Replaced CVM by a more industrial version
3. Added drain valve on cathode inlet, mounted on system plate
4. Increased coolant volume in the system plate
5. Replaced ECU and wiring harness
6. Replaced Humidifier
7. Protected the + and – contact of the fuel cell
8. Added cells protection on the side
9. Replaced compressor by air bearing compressor

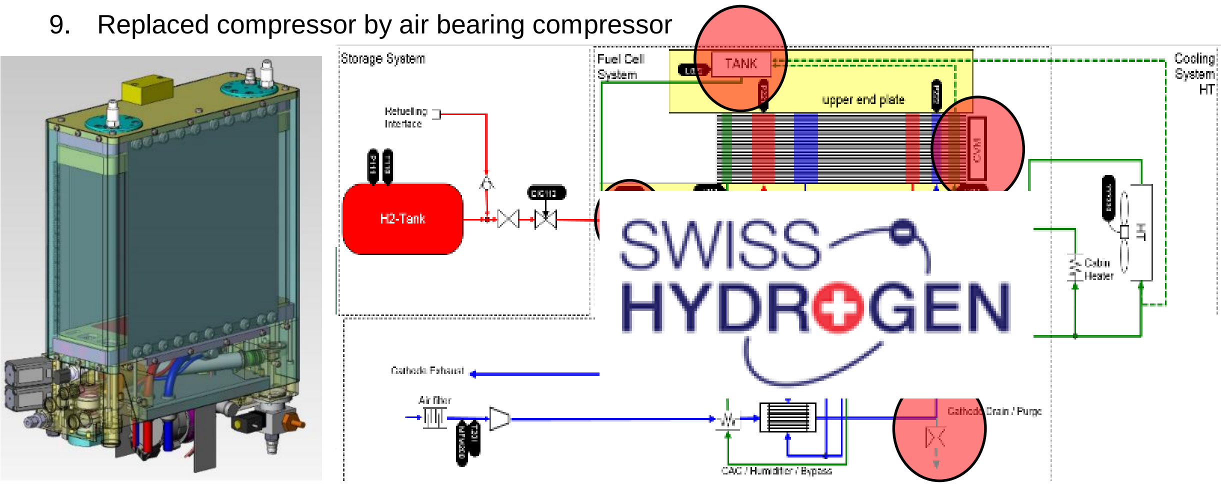


Fig 13 : CAD drawing of the FCS (left) and its redesign points (right).

The fuel cell stack was increased from 80 cells (in the Fiat) to 94 cells in order to use a more industrial CVM developed for another application.

As shown in Fig. 14, the fuel cell stack was able to produce up to 12 kW above 0.65V per cell.

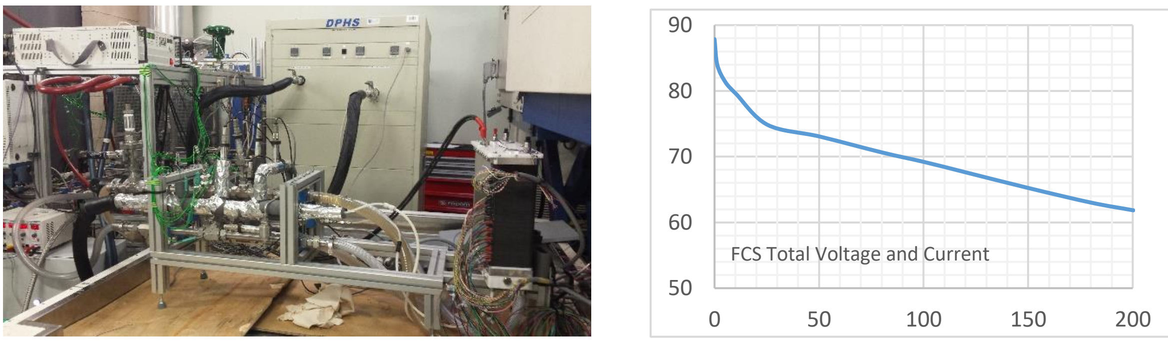


Fig 14: The 10kW fuel cell stack on the test bench at Belfort UTBM and its polarization curve.

For integration into the vehicle, we first had to study all the 3D files of the Kangoo ZE received from Renault. This phase was extremely complex as the Renault 3D drawings are a mixture between the normal Kangoo with a gasoline engine and the electric version. In addition, we received all the files in Catia which had to be converted to our Inventor CAD software.

Finally, we could extract all the necessary files and work on preliminary 3D integration of the main fuel cell system components. At the end of this exercise, we could already realize that there will be not much room left in engine compartment of the Kangoo ZE (see Fig. 15).

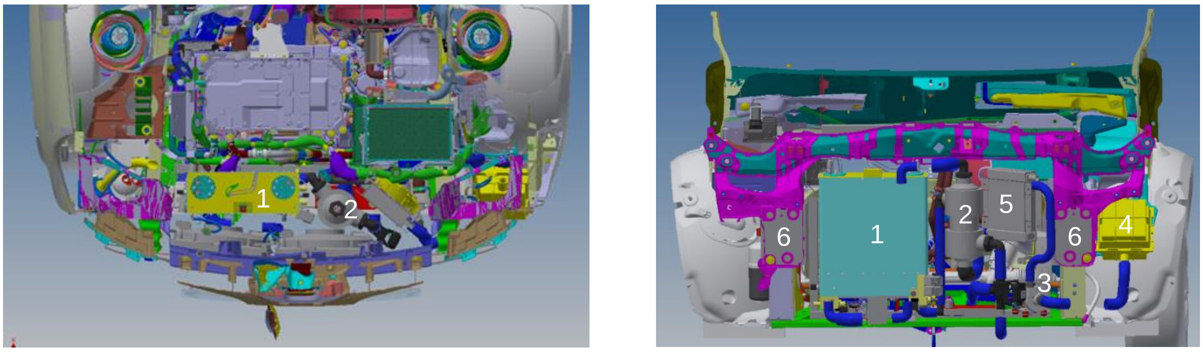


Fig 15: The 3D integration trials into the engine compartment, with fuel cell (1), humidifier (2), compressor (3), air filter (4), and charge air cooler (5).

We have tried not to modify the structure of the car except for a few plastic fixation bars. On the other hand, with the aim to have a very secure fixation for the entire fuel cell system, we decided to use the same fixation points of the front bumper (number (6) on Fig. 15).

Once this approach was validated by Renault, we have designed the main fixation parts that had to be realized in stainless-steel to support the weight of the fuel cell (see Fig. 16).

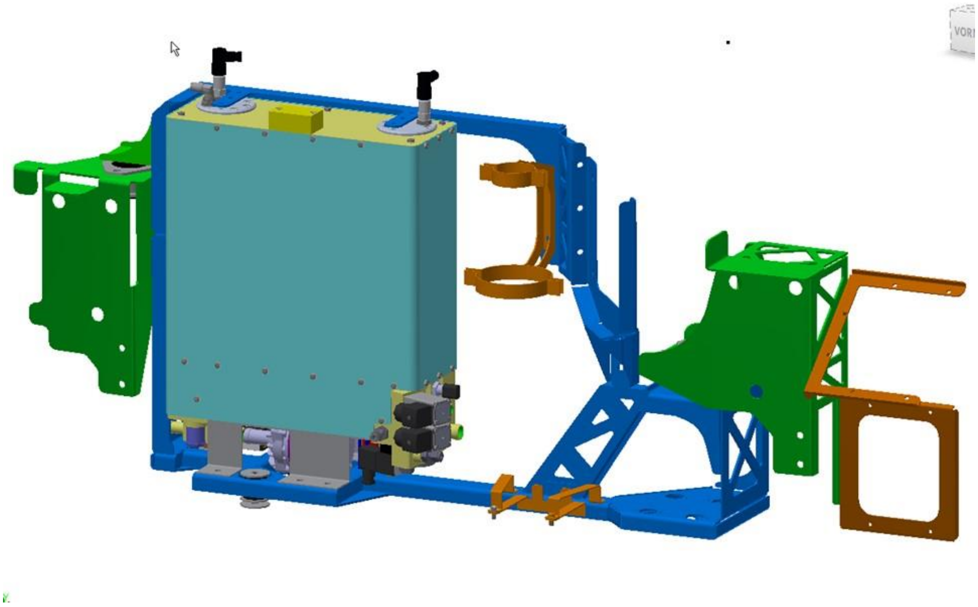


Fig 16: The CAD of the fixation parts for the fuel cell system for its integration into the vehicle.

Once the integration concept was validated by Renault, the main fixation parts have been realized in stainless-steel to support the weight of the fuel cell stack (1). Additional fixation parts had to be designed to support the controller (7), the DC/DC converter (8), and the HSL LV-junction box (9) (see Fig. 17).

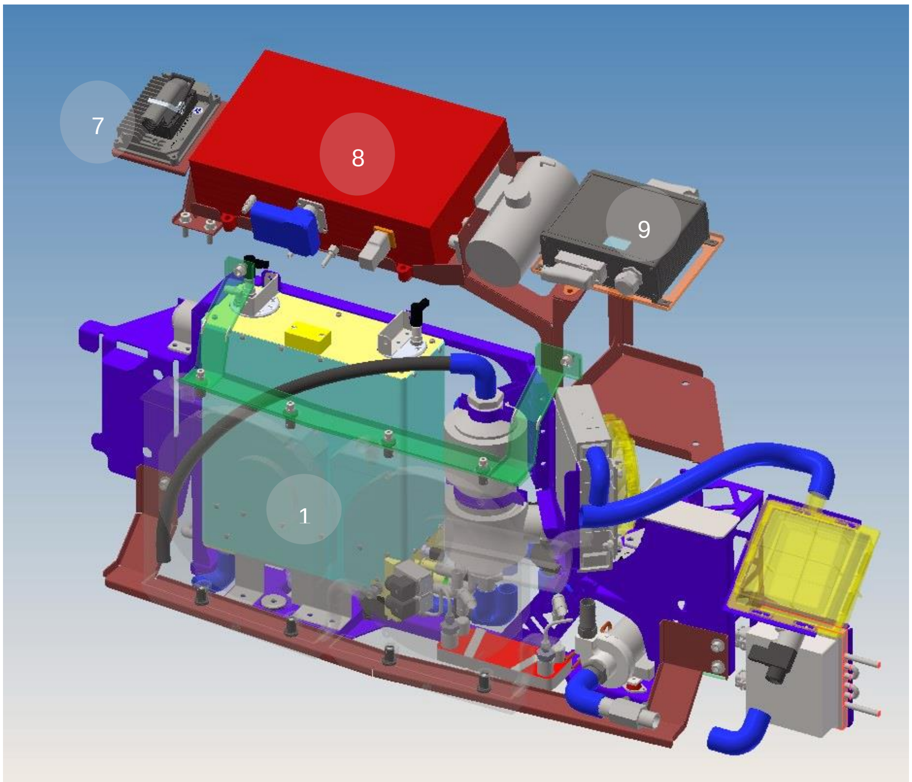


Fig 17 : The CAD of the complete FCS as integrated into the vehicle.

All the stainless steel fixation parts have been manufactured by sheet bending and welding. To receive these parts, the front of the vehicle was completely dismantled. The parts were mounted one by one and numerous adaptation had to be made, since the 3D designed delivered by Renault were not always exhaustive.

The plastic parts modifications were necessary to accommodate the room for two radiators replacing the original Renault radiator. Since the fuel cell operates at a higher temperature than the electronic, it is necessary to have two cooling loops with two separate radiators. Fig. 18 shows the mounting of the parts on the front bumper fixation (6) with the humidifier (2) and the air compressor (3) already mounted. Fig. 19 shows the mounting of all the fixation parts, with the controller (7), the DCDC (8), and the two radiators (10) already fixed.

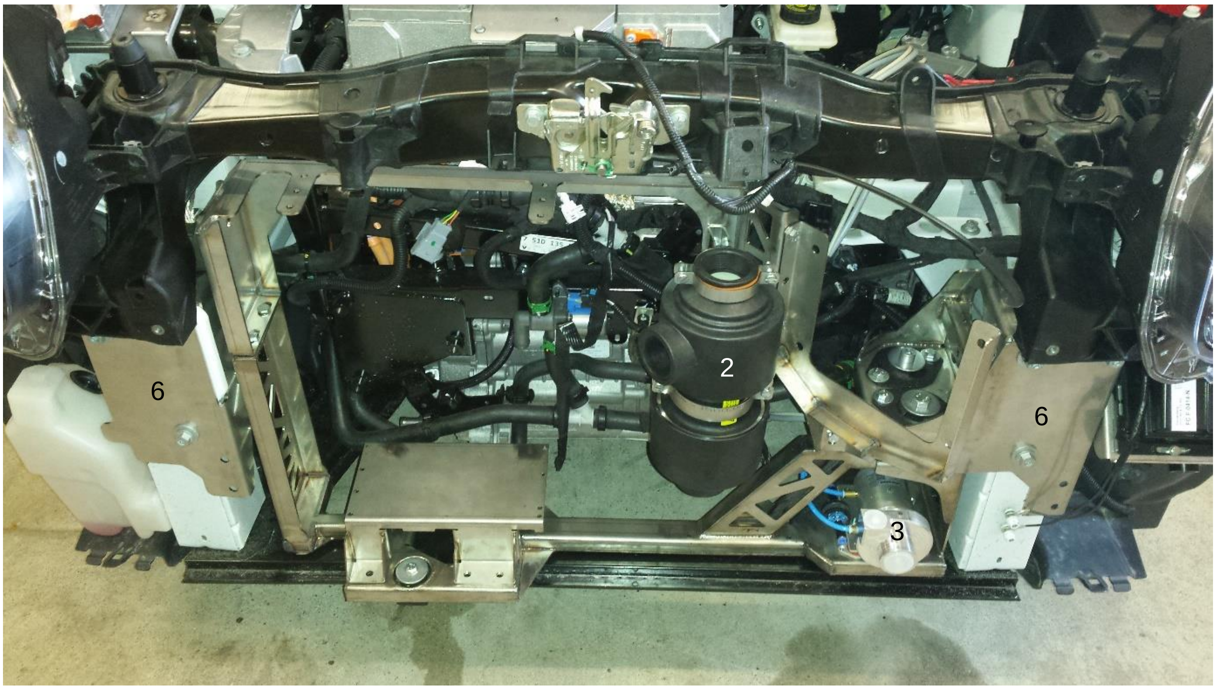


Fig 18: Mounting of the fixation structure screwed on the front bumper bars with the humidifier and air compressor already fixed.

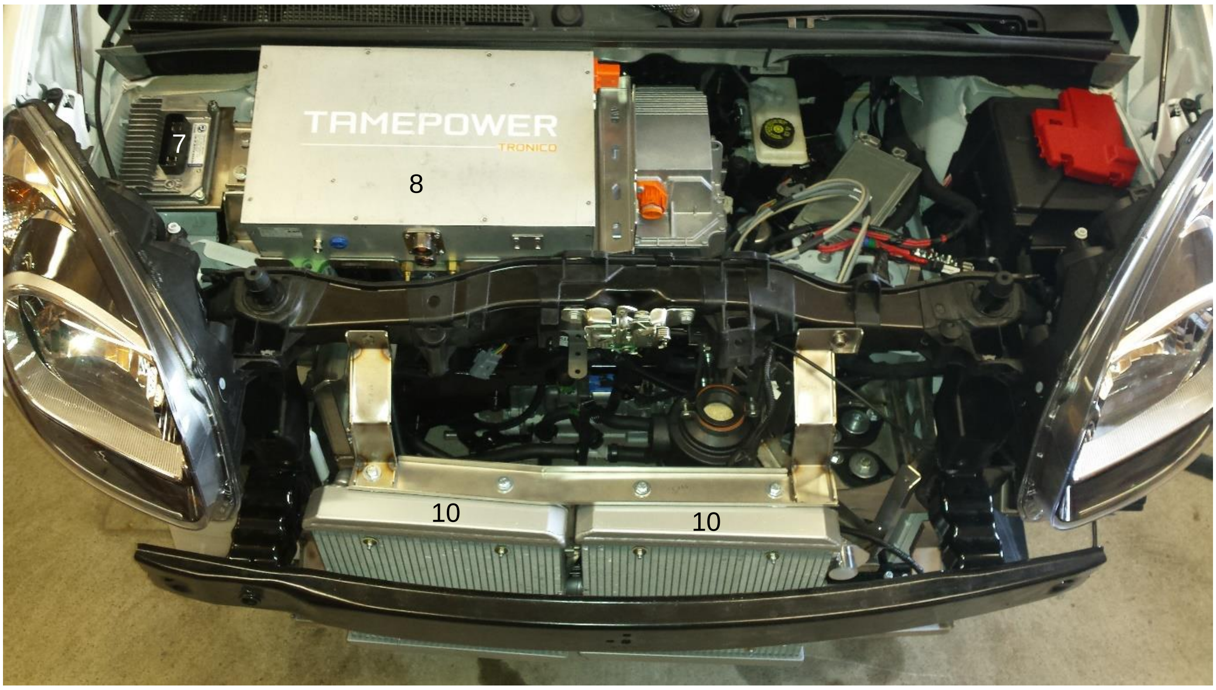


Fig 19: Mounting of all the fixation parts, with the controller (7), the DCDC (8), and the two radiators (10, high temperature right side driving direction, low temperature left side driving direction).

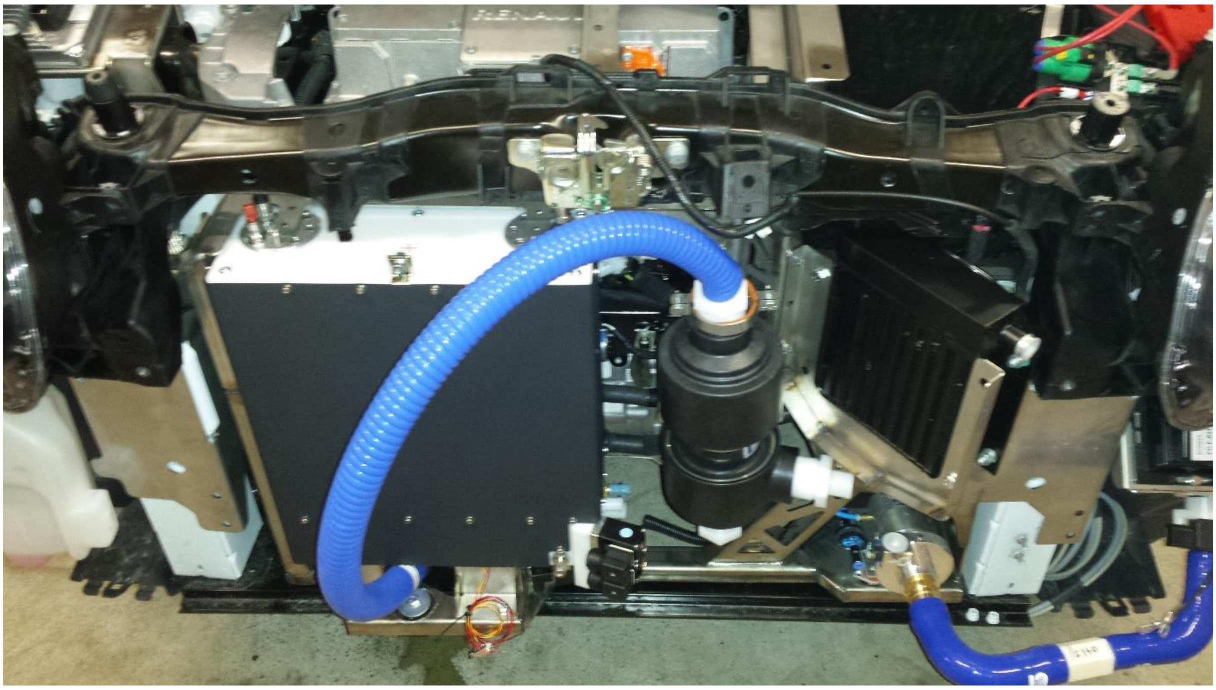


Fig 20: Mounting of the fuel cell stack with pre-connected air loop.

The air loop starts with the air filter (Fig. 21 left), then it goes to the compressor, followed by the charge air cooler (Fig. 21 right.), to lower the temperature before it enters the humidifier, and finally through the humidifier before entering the fuel cell stack.

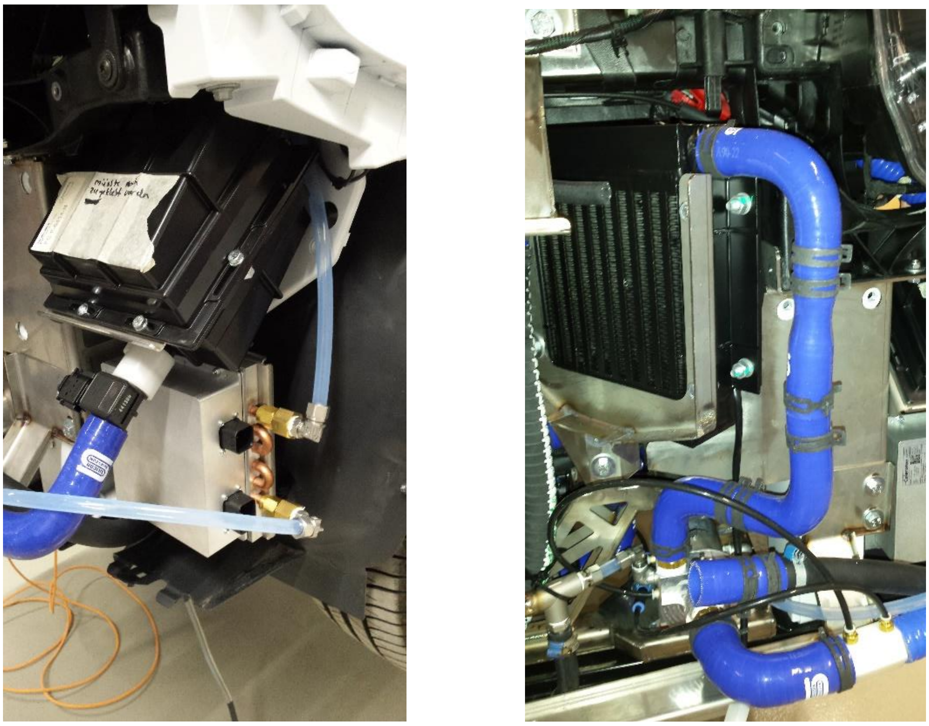


Fig 21: Air filter and underneath the compressor inverter with coolant in and out (left); charge-air cooler following compressor's output (right).

Once completely mounted, the fuel cell itself can hardly be seen, packaged as it is between the radiators and the DC/DC and junction boxes (Fig. 22).

Fig 22 : Completely mounted system within the engine compartment of the Renault Kangoo ZE.

3.2 Electrical Integration

3.2.1 High voltage cabling architecture

In order to start the Celeroton compressor, its inverter need to be powered from the 12 volt battery. Once the fuel cell is in operation, the compressor runs on the fuel cell voltage to get its maximum power output.

Since the fuel cell voltage is lower than the battery voltage, the fuel cell is connected to a DCDC provided by the company Tronico.

Once the fuel cell power is at the right voltage it can be injected on the battery bus, the energy will be directly consumed by the electric motor when the vehicle is in traction mode, else the electric energy generated by the fuel cell will recharge the battery.

In order to access the 400V DC bus we connect to the Renault high voltage junction box at the place of the potential temperature control (CTP) as we verified that this line can take up to 30A (12kW@400V). For this connection, a dedicated junction box was designed and realized with appropriate fuses (see Fig. 24). After construction, this dedicated junction box was installed under the car within the middle tunnel.

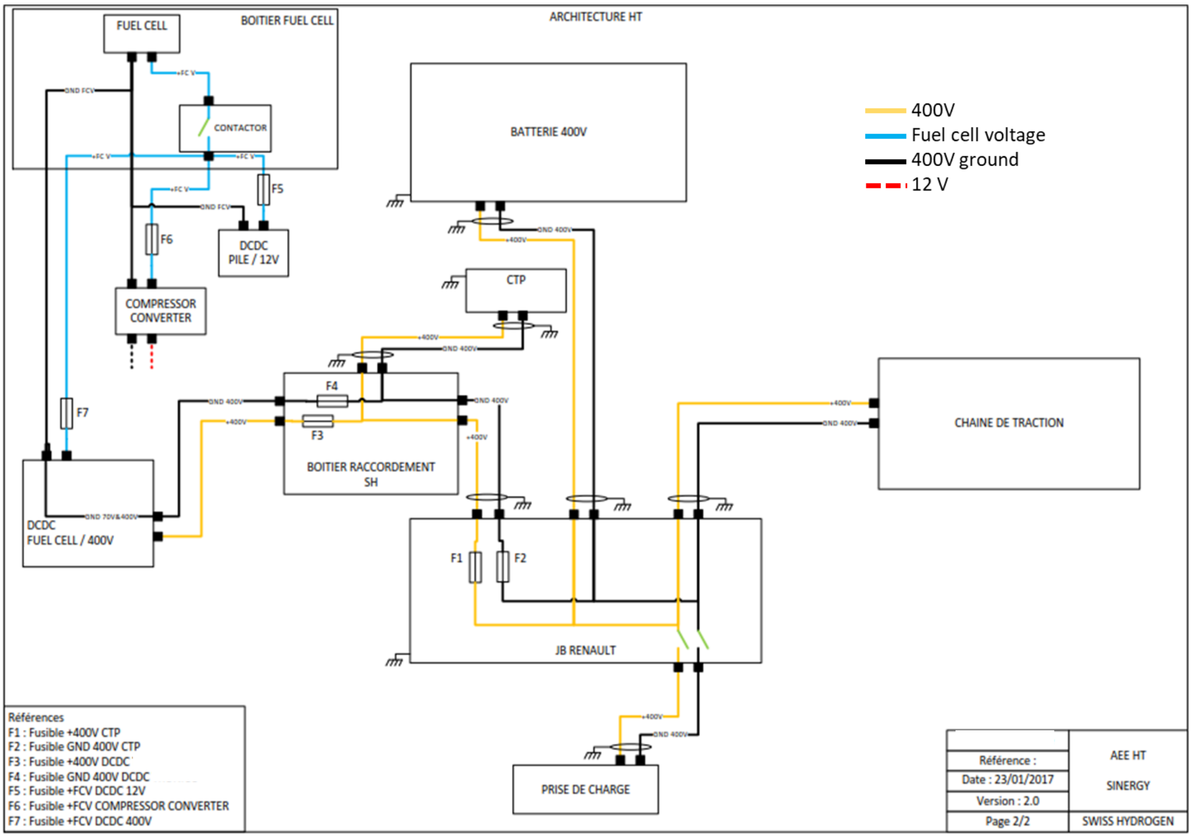


Fig 23 : High voltage cabling schematics including the position of every safety fuses.

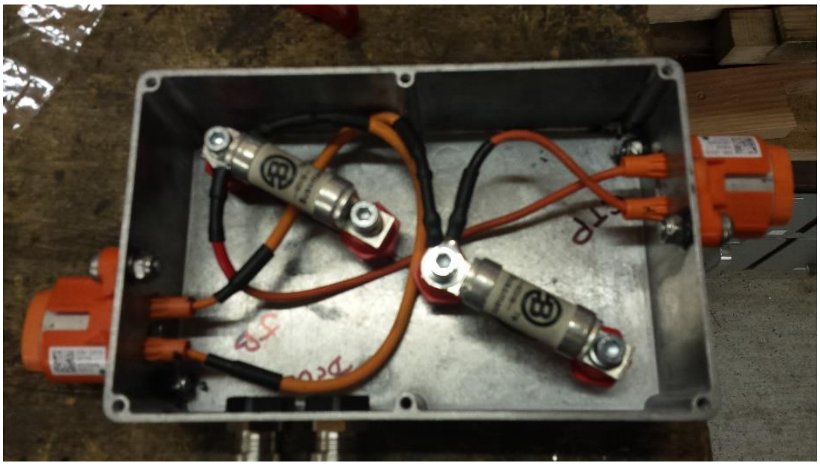


Fig 24 : High voltage junction box to connect fuel cell output into CTP plug with safety fuses.

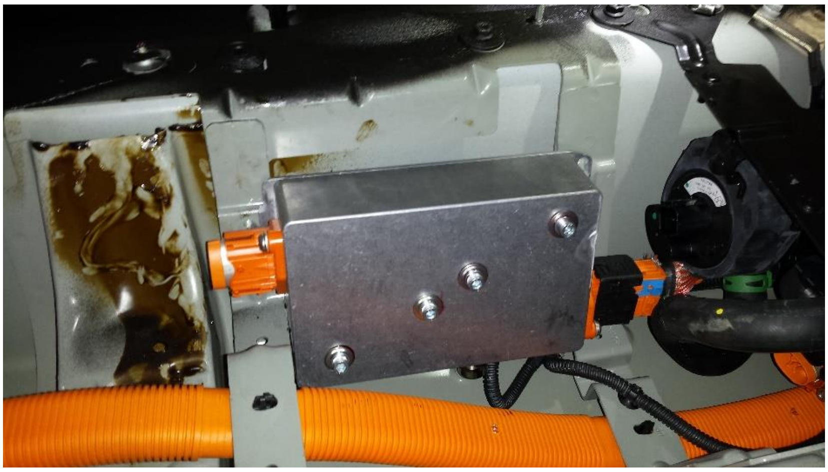


Fig 25 : High voltage junction box fixed under the car within the chassis tunnel.

3.2.2 Low voltage junction-box and Hardware Safety Layer

The low voltage junction box links/routes the fuel cell systems to the 12V signals of the vehicle. The box also distributes the 12V to the fuel cell ECU.

In addition, the LV junction box should integrate the function of the HSL (Hardware Safety Layer). The HSL has the main function of closing the H2 supply from the tank if a H_2 leak is detected.

The partial schematics of the low voltage junction box and HSL can be seen in Fig. 27.

In addition, the low voltage wiring harnesses was realized and integrated into the vehicle. The LV wiring harness concerns the cables connected to the LV junction box.

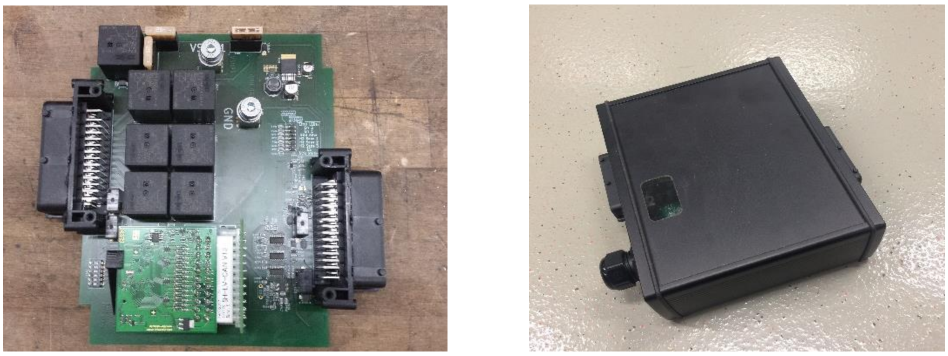


Fig. 26: Low voltage junction-box and HSL.

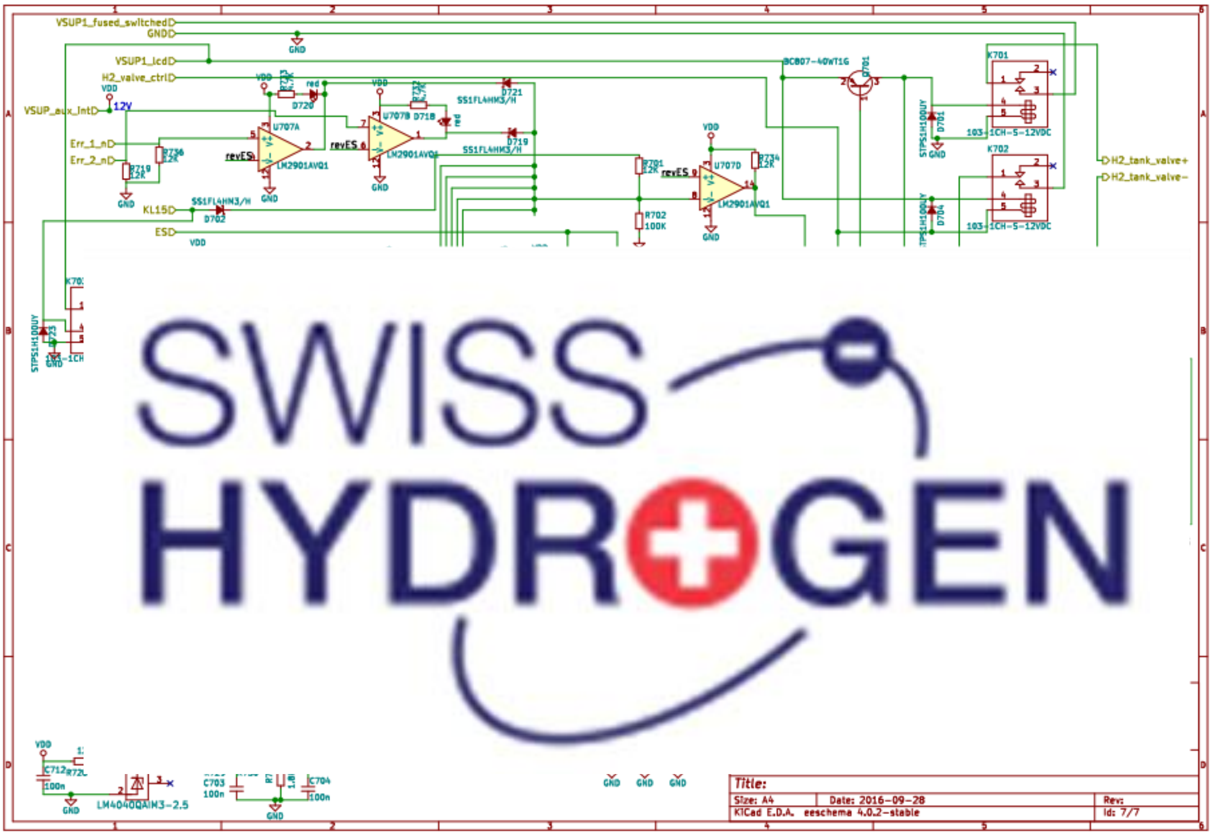


Fig 27 : Schematics of the low voltage junction box with the function of Hardware Safety Layer.

3.2.3 CAN Bus communication

The fuel cell system, including CVM, compressor and all the actuators communicate with CAN protocol centralised by the ECU. Then this ECU also communicates with the DC/DC converter, the HSL and the man-machine interface for a smooth operation of the fuel cell. Fig. 28 shows the complete schematics of the CAN bus communication within the vehicle.

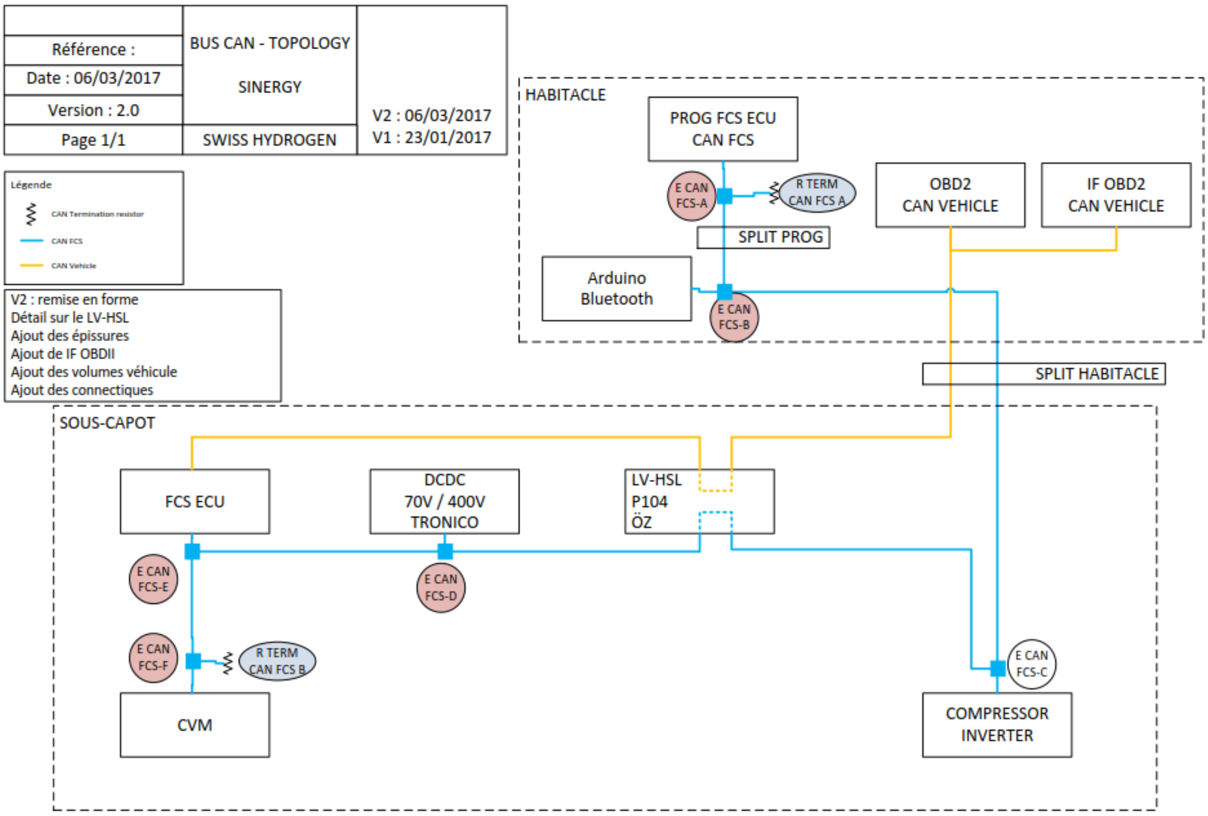


Fig 28 : Schematics of the CAN bus.

4 Resources and homologations

4.1 Resources

Most of the delivered work has been achieved by Swiss Hydrogen, typically its fuel cell laboratory and test benches, garage, workshop, data acquisition, processing and analysis, and CAD.

Two subcontractors have been involved in the project:

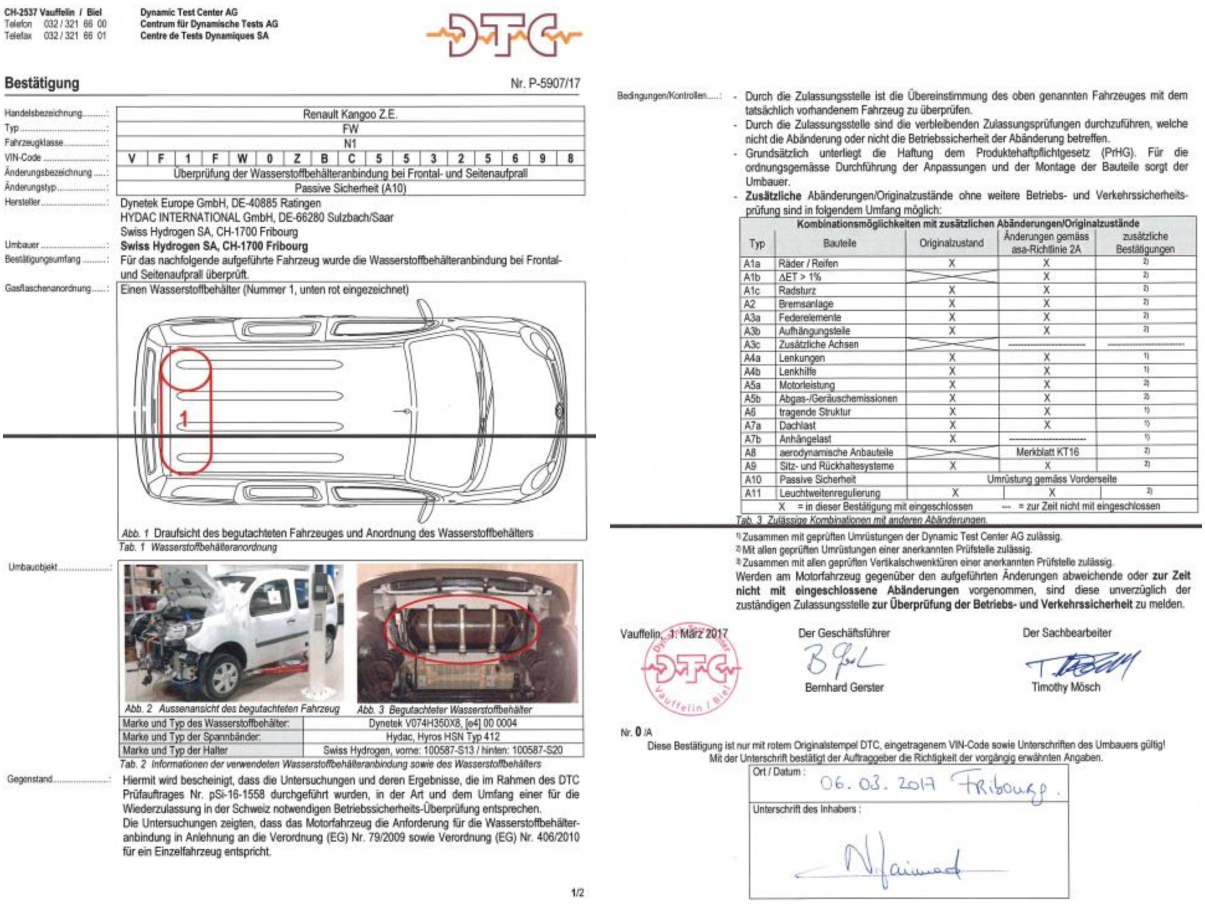
1. Ökozentrum, Langenbruck (CH): Externalized work on mechanics and electrics. CAD, garage, workshop, electronic workshop.
2. CRSM Bureau Technique H. de Bros (CH): Externalized work on CAD for the fuel cell system redesign.

The key suppliers were:

1. Renault Group, Guyancourt (F): Designer of the Kangoo ZE and technical support.
2. Celeroton, Zurich (CH): High speed compressor with integrated air bearings.
3. Tronico, Nantes (F): DC/DC converter supplier.

4.2 Mechanical homologation

Following the analysis of our FEM simulation as well as a physical control of the vehicle, the Dynamic Test Center (DTC) has delivered a positive certificate necessary for the homologation of the vehicle.



CH-2537 Vauffelin / Biel
Telefon 032 / 321 66 00
Telefax 032 / 321 66 01

Dynamic Test Center AG
Centrum für Dynamische Tests AG
Centre de Tests Dynamiques SA

Bestätigung Nr. P-5907/17

Handelsbezeichnung:	Renault Kangoo Z.E.
Typ:	FW
Fahrzeugklasse:	N1
VIN-Code:	V F 1 F W 0 Z B C 5 5 3 2 5 6 9 8
Änderungsbezeichnung:	Überprüfung der Wasserstoffbehälteranbindung bei Frontal- und Seitenaufprall
Änderungstyp:	Passive Sicherheit (A10)

Hersteller: Dynetek Europe GmbH, DE-40885 Ratingen
HYDAC INTERNATIONAL GmbH, DE-66280 Sulzbach/Saar
Swiss Hydrogen SA, CH-1700 Fribourg

Umbauer: **Swiss Hydrogen SA, CH-1700 Fribourg**

Bestätigungsumfang: Für das nachfolgende aufgeführte Fahrzeug wurde die Wasserstoffbehälteranbindung bei Frontal- und Seitenaufprall überprüft.

Gasflaschenanordnung: Einen Wasserstoffbehälter (Nummer 1, unten rot eingezeichnet)

1

Abb. 1 Draufsicht des begutachteten Fahrzeuges und Anordnung des Wasserstoffbehälters
Tab. 1 Wasserstoffbehälteranordnung

Umbauobjekt:

Abb. 2 Aussenansicht des begutachteten Fahrzeug
Abb. 3 Begutachteter Wasserstoffbehälter

Marke und Typ des Wasserstoffbehälter:	Dynetek V074H350X8, [e4] 00 0004
Marke und Typ der Spannbänder:	Hydac, Hyros HSN Typ 412
Marke und Typ der Halter	Swiss Hydrogen, vorne: 100587-S13 / hinten: 100587-S20

Tab. 2 Informationen der verwendeten Wasserstoffbehälteranbindung sowie des Wasserstoffbehälters

Gegenstand: Hiermit wird bescheinigt, dass die Untersuchungen und deren Ergebnisse, die im Rahmen des DTC Prüfauftrages Nr. pSi-16-1558 durchgeführt wurden, in der Art und dem Umfang einer für die Wiederzulassung in der Schweiz notwendigen Betriebssicherheits-Überprüfung entsprechen.
Die Untersuchungen zeigten, dass das Motorfahrzeug die Anforderung für die Wasserstoffbehälteranbindung in Anlehnung an die Verordnung (EG) Nr. 79/2009 sowie Verordnung (EG) Nr. 406/2010 für ein Einzelfahrzeug entspricht.

1/2

Bedingungen/Kontrollen:
- Durch die Zulassungsstelle ist die Übereinstimmung des oben genannten Fahrzeuges mit dem tatsächlich vorhandenem Fahrzeug zu überprüfen.
- Durch die Zulassungsstelle sind die verbleibenden Zulassungsprüfungen durchzuführen, welche nicht die Abänderung oder nicht die Betriebssicherheit der Abänderung betreffen.
- Grundsätzlich unterliegt die Haftung dem Produktehaftpflichtgesetz (PrHG). Für die ordnungsgemässe Durchführung der Anpassungen und der Montage der Bauteile sorgt der Umbauer.
- **Zusätzliche** Abänderungen/Originalzustände ohne weitere Betriebs- und Verkehrssicherheitsprüfung sind in folgendem Umfang möglich:

Kombinationsmöglichkeiten mit zusätzlichen Abänderungen/Originalzustände				
Typ	Bauteile	Originalzustand	Änderungen gemäss asa-Richtlinie 2A	zusätzliche Bestätigungen
A1a	Räder / Reifen	X	X	2)
A1b	ΔET > 1%		X	2)
A1c	Radsturz	X	X	2)
A2	Bremsanlage	X	X	2)
A3a	Federelemente	X	X	2)
A3b	Aufhängungsteile	X	X	2)
A3c	Zusätzliche Achsen		----------	----------
A4a	Lenkungen	X	X	1)
A4b	Lenkhilfe	X	X	1)
A5a	Motorleistung	X	X	2)
A5b	Abgas-/Geräuschemissionen	X	X	2)
A6	tragende Struktur	X	X	1)
A7a	Dachlast	X	X	1)
A7b	Anhängelast	X	----------	1)
A8	aerodynamische Anbauteile		Merkblatt KT16	2)
A9	Sitz- und Rückhaltesysteme	X	X	2)
A10	Passive Sicherheit	Umrüstung gemäss Vorderseite		
A11	Leuchtweitenregulierung	X	X	2)
X = in dieser Bestätigung mit eingeschlossen		--- = zur Zeit nicht mit eingeschlossen		

Tab. 3 Zulässige Kombinationen mit anderen Abänderungen.

1) Zusammen mit geprüften Umrüstungen der Dynamic Test Center AG zulässig.
2) Mit allen geprüften Umrüstungen einer anerkannten Prüfstelle zulässig.
3) Zusammen mit allen geprüften Vertikalschwenktüren einer anerkannten Prüfstelle zulässig.
Werden am Motorfahrzeug gegenüber den aufgeführten Änderungen abweichende oder **zur Zeit nicht mit eingeschlossene Abänderungen** vorgenommen, sind diese unverzüglich der zuständigen Zulassungsstelle **zur Überprüfung der Betriebs- und Verkehrssicherheit** zu melden.

Vauffelin, 1. März 2017

Der Geschäftsführer
Bernhard Gerster

Der Sachbearbeiter
Timothy Mösch

Nr. **0** /A
Diese Bestätigung ist nur mit rotem Originalstempel DTC, eingetragenem VIN-Code sowie Unterschriften des Umbauers gültig!
Mit der Unterschrift bestätigt der Auftraggeber die Richtigkeit der vorgängig erwähnten Angaben.

Ort / Datum : 06. 03. 2017 Fribourg.
Unterschrift des Inhabers :

Fig 29: Positive report from the DTC.

4.3 Electric homologation

An other certificate is necessary for the homologation of the vehicle and it concerns the high voltage electric cabling. This cabling has to be verified by a certified body. In our case we have chosen the organisation Electrosuisse. After thorough inspection of the vehicle and all the details of the modified high voltage cabling, Electrosuisse delivered as well a positive report.

With these two reports, we were able to obtain normal number plates for this Hydrogen Kangoo ZE.

Konformitätsbewertung **Ref. 16-IK-0163.S01**

Prüfbericht	Fehraltorf, 6. März 2017
Auftragsdatum:	14. 12. 2016
Referenz:	Frau Nafissa Haimad
Auftraggeber:	Swiss Hydrogen SA Fribourg, SWITZERLAND
Hersteller:	Renault and Swiss Hydrogen SA
Gegenstand:	
Handelsmarke:	Renault
Typ:	Kangoo Z.E. HY-REX10 Chassis VF1FW0ZBC553256
Techn. Daten:	Antriebsbatterie 400 V / 22 kWh Elektromotor 400 V / 44 kW
Prüfung:	Sicherheitstechnische Prüfung des Traktionsnetzes (> 2 Amp.)
Prüfbestimmung:	UN ECE R100 Absatz 5.1 Revision 02 incl. Suppl. 01 und 02 Das Fahrzeug ist bereits homologiert. Nur das Brennstoffzellensystem wurde zusätzlich installiert, was die Prüfung der zusätzlichen Teile und deren Einbau im Fahrzeug nötig macht.
Ergebnis:	Prüfung bestanden

Electrosuisse
Produktequalifizierung PZ-IK

Matthias Huber, Prüfingenieur

Remo Egger, Laborleiter

Fig 30: Positive report from Electro Suisse.

Fig 31: Number plates obtained after homologation of the vehicle.

5 Drive and performance analysis

The vehicle has been delivered to the energy utility company Sinergy SA based in Martigny on September 2017. The hydrogen fueling station of the Wallis Swiss Federal Institute of Technology inaugurated on September 9th, 2016 is providing the gas with a fast refueling service for the 350bar. At its delivery, the car was filled up at the SHSA hydrogen fueling station.

5.1 Control and command interface

The working principle of this interface is described in Figure 32.

The control and command interface relies on an Android smartphone (1). The Android operating system offers all the required functionalities:

- Graphic design
- Logic Software
- Bluetooth communication
- WIFI/GSM communication
- Real Time Manager
- Data logger/Live data on server
- On Board Diagnostic

A Bluetooth connection must be established between the FCS and the interface in order to operate it. A Bluetooth module (2), a CAN Bus shield (3) and a low consumption microcontroller 'Arduino Uno' (4) have been installed in the car. This represents a very affordable solution to operate the FCS.

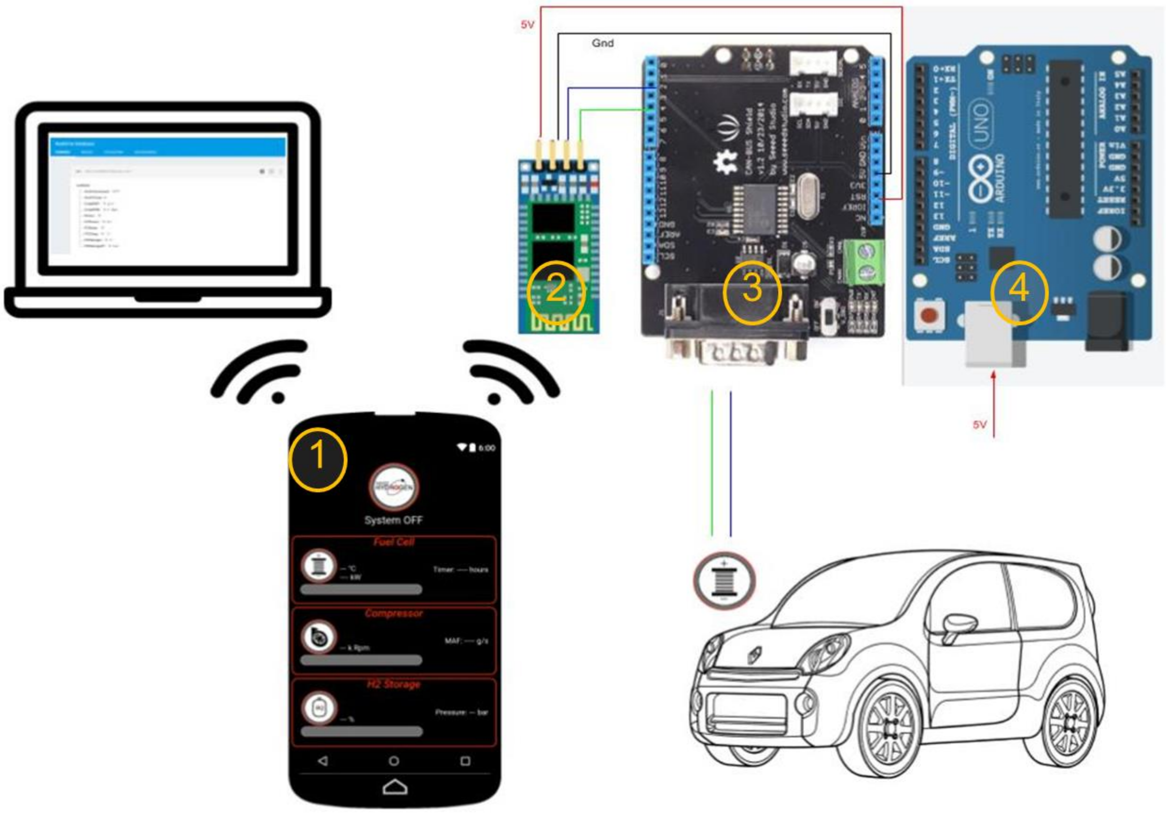


Fig 32 : Control and command interface concept

Many operational parameters of the FCS are stored on board on a SD memory card. The recording frequency is related to the CAN bus one and represents thousands of parameters recorded by second.

Unfortunately, the data logger can’t access to the car information like covered distance, vehicle speed, consumed power by the electrical engine. The recorded data are related to the following FCS component:

1. DC/DC converter
2. FCS
3. Storage
4. Compressor
5. HSL
6. ECU
7. CVM

Fig 33: Typical display of the user interface while the FCS in operation.

Some data treatments and analysis are presented in section 5.2

5.2 Drive data and analysis

The data logger is permanently recording all FCS parameters. The FCS presents different state of operations presented in the table below:

0	OFF
1	Init (controller Power ON)
2	Standby
3	Starting ...
4	ON
5	Drying FC ...
6	Shutdown
7	(rfu)
8	(rfu)
9	Locked out (by ES)
10	Emergency Stop

Fig 34: FCS state description

The graphs presented in this section have been generated on a drive run of about 1.5 hours on June 19th, 2018. The analyses are achieved with a time step of 30seconds (all recorded parameters are averaged on this period).

It should be noted that Renault did not deliver yet its official authorization to inject the FCS full power to the FCS. In the context, the output power of the DC/DC inverter has been limited for now to 6 kW maximum to preserve the electrical circuit of the car from too high current.

The work achieved by Swiss Hydrogen SA allows to access to main data of the car like, vehicle speed, traveled distance, state of charge of the main battery, and traction power (negative when recharging the battery), as illustrated in Figure 35.

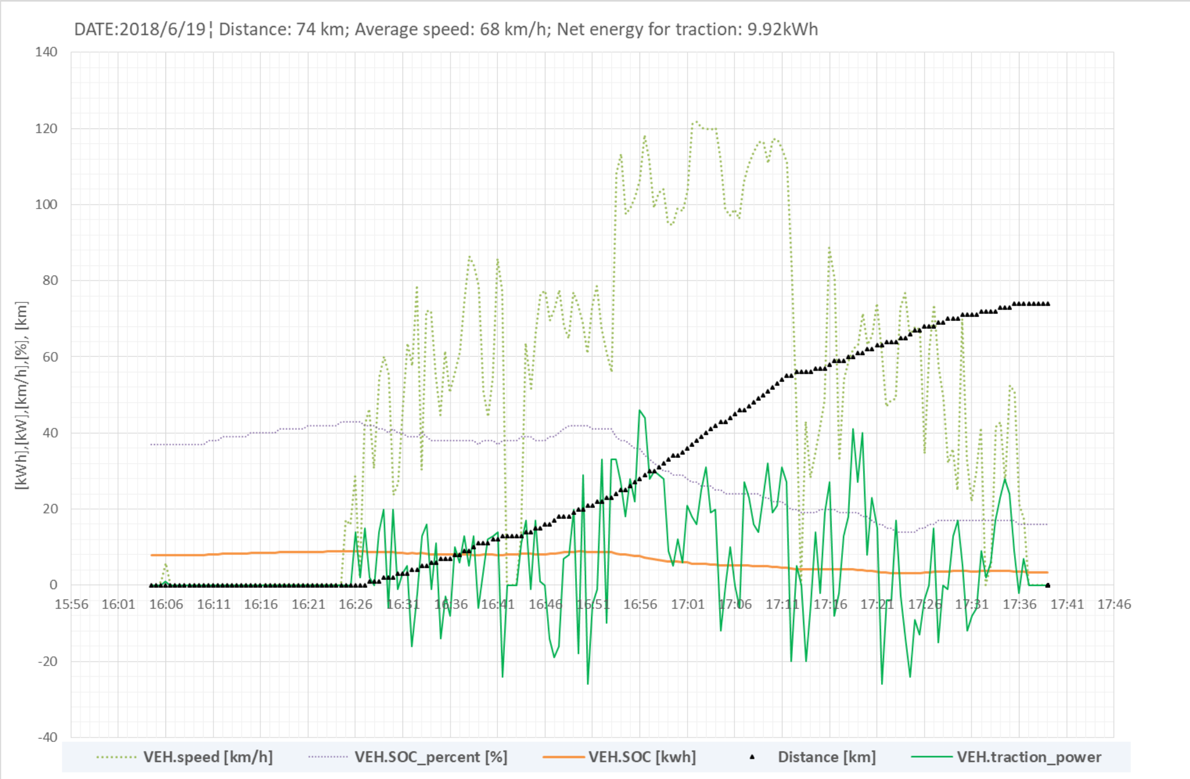


Fig 35: General vehicle information

The data treatment software calculates some main run values, such as the total travelled distance (here, 74 km), the average speed (68 km/h, highway was part of the drive) and the net energy flow for the propulsion drive chain (9.9 kWh while 13.3kWh was consumed by the propulsion engine and 3.4 kWh generated during deceleration phase).

The drive started with 7.8 kWh of SOC and arrived with 3.3 kWh (using 20% of the battery energy storage capacity). These values show that this distance could not have been covered without the hydrogen range extender.

The output power of the FCS is included in Figure 36. The produced electrical energy on the drive run of 10.1 kWh is a bit higher than the energy net flux of the vehicle. During the 20 first minutes, the FCS works while the vehicle is stopped, the operating strategy of the system limits the FCS output power to 4 kW, the SOC of the battery increases consequently.

On figure 37 is presented the DC/DC inverter and FCS output power with the 1kW air bearing compressor rotation speed. While absorbing 500 W at 200’000 rpm when the FCS is delivering 4 kW (here, the FCS sub components absorb up to 13% of the FCS output power), the compressor turns at a full speed of 280’000 rpm when FCS produces close to 8kW, the ratio between FCS and DC/DC inverter energy output is then decreased to 81%.

Some adjustments of the FCS working parameters have been done to insure a proper functioning during the winter season and must be optimized on a longer period of return of experience to improve the system efficiency. Typically, system purge frequency and cooling strategy are concerned.

This data analysis allows to better undestand and to optimize the working parameters of the system in real conditions in a wide spread meteorogical conditions offered by the Wallis region.

5.3 User feedback

« J’ai eu la chance, dans le cadre de mon travail de monteur électricien, de pouvoir conduire la Kangoo H2 à plusieurs reprises. C’est une sensation rassurante que de savoir qu’on ne restera pas bloqué à mi-chemin faute de batterie grâce au kit hydrogène installé. En effet, l’autonomie de la Kangoo ZE est trop limitée pour une utilisation professionnelle. L’emploi du « kit hydrogène » est très simple et ludique. Il suffit d’appuyer sur l’écran pour allumer la pile à combustible et se voir octroyer des km d’autonomie supplémentaires et ainsi parvenir à bon port. Lorsque la pile est allumée, hormis l’indicateur de l’interface, il n’y a pas moyen de se rendre compte qu’elle est allumée, si ce n’est un léger ronronnement qui se fait entendre. Le plein d’hydrogène est très rapide. En quelques minutes seulement nous voilà reparti pour 170km. J’espère qu’à terme nous en aurons tous une ! »

Christophe Boullot

Responsable compteurs manifestation et IP, Sinergy SA

6 Discussion of results

The presented data concern a limited period but show the evolution of main system parameters with time.

The exhaustive list of the 95 recorded parameters is illustrated below:

DCDC (7)	FCS (15)	STO (3)	CMP (7)	CVM (56)	VEH (7)
1 power	1 FCS_state	1 H2_level	1 speed	1 Error	1 aux_pwr
2 I_in	2 WL2_register	2 H2_press	2 status_1	2 Firmware‘urerginn	2 speed
3 I_out	3 Warning Level	3 H2_temp_high	3 status_2	3 Initializecl	3 steering_angle
4 U_in	4 I_S		4 information_code	4 SamplingTime	4 traction_power
5 U_out	5 U_S		5 warning_code	5 SendValue	5 SOC
6 Int_Supply_Voltage	6 p_SI_A		6 error_1	6 Serial	6 SOC_percent
7 T_coolant	7 p_SI_C		7 error_2	7 ShuntExternal	7 odometer
8 T_pcb	8 F_SI_C		8 I_in_battery	8 ShuntInternal	
9 error	9 T_Si_CL		9 I_in_fuelcell	9 MaxChannelPosition	
10 status	10 T_So_CL		10 ParamID	10 MaxChannelVoltage	
	11 c_S		11 U_in_Battery	11 MinChannelPosition	
	12 h_S		12 U_in_fuelcell	12 MinChannelVoltage	
	13 power		13 Value	13 TotalVoltageSum	
	14 T_Amb		14 converter_temp	14 MeanVoltage	
	15 T_HUMi_C		15 dc_link_current	15 Reserved_word4_312	
	16 bypass_valve_pos		16 dc_link_current_reference	16 StdDev	
	17 sp_coolpump		17 dc_link_voltage	17 TotalVoltageMeasured	
			18 motor_temp	18 ImpedanceARG	
			19 phase_current	19 ImpedanceABS	
			20 phase_voltage	20 Reserved_word3_313	
			21 power	21 Reserved_word4_313	
			22 reference_speed	22 TemperatureCPU	
				23 Temperature_ADC00	
				... ...	
				37 Temperature_ADC14	
				38 Temperature_NTC00	
				... ...	
				45 Temperature_NTC07	
				46 ThermalShutdown	
				47 Channel_00	
				... ...	
				94 Channel_47	

Fig36: List of recorded parameters by the on-board data logging system (blue marked values are systematically plotted and analyzed over time)

All data are recorded on board on a SD card where the log files since the first testing are present. From the delivery to the final customer, this card is regularly swapped with another one keep at SHSA office for analysis and system improvement, and assessment of the performance with time.
The parameters highlighted in blue will be systematically analysed thanks to an automatic treatment with an excel file. All copy of the data and analysis are stored on the company’s server.

7 Conclusions and outlook

The mechanical and electrical integration of a fuel cell system in a commercially available Renault car has been achieved in this project.

Some delays in the final delivery have been observed mainly related to the late reception of Renault information required to modify the car for the tank integration or to access to the confidential data of the car management system.

However a first return of experience by the final customer reflects full satisfaction of the performance and range increase allowed by the FC system.

Major achievements consist in:

- The mechanical integration of the FCS and its sub components and the power management electronics in the remaining empty volumes let by the thermal engine in a very tiny environment
- The electrical integration of the control systems and the successful access to some main parameters of the CAN bus of the car
- The authorization to obtain standard plate number by the Swiss road administration
- The comfort of use offered by a simplified interface with main parameters displayed on a smartphone

This realization will serve over the years two objectives as a demonstrator of a zero emission hybrid fuel vehicle based on PEM technology and as a testing laboratory in real conditions for an extended return of experience of such a promising system.

7.1 Next steps after end of project

Due to the innovative nature of this work, some interactive actions will occur with the final customer. A whole year minimum of testing will be required to have a consolidated overview of the performances and impacts of ambient parameters.

A major improvements will be also achieved when increasing the power output of the system once the current limitation to 6kW of injected power will be raised by Renault.

Swiss Hydrogen SA thanks the Swiss Federal Office of Energy for its support.