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INN-BALANCE Guidebook

Improvement of Balance of Plant Components for PEM based automotive fuel cell systems

INN·BALANCE
AUTOMOTIVE FUEL CELL

FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

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List of Abbreviations

BoP	Balance of plant
CAD	Computer-aided design
CFD	Computational fluid dynamics
DC	Direct current
FC	Fuel cell
FCEV	Fuel cell electric vehicle
FCH JU	Fuel cells and hydrogen joint undertaking
GHG	Greenhouse gases
H2	Hydrogen
HIL	Hardware in the loop
HW	Hardware
ICE	Internal combustion engine
NVH	Noise, Vibration, Harshness
PEM	Proton-exchange membrane
RPEMS	Rapid prototyping engine management system
SW	Software
THDA	Total harmonic distortion analysis
TRL	Technology readiness level
WLTC	Worldwide harmonized light vehicles test cycles

Abstract

INN-BALANCE in a nutshell

Fuel cells are a mature technology ready for scale-up in the automotive market. It is now about advancing manufacturing through reducing costs of production, while increasing the overall efficiency and reliability of fuel cell systems in cars. These are the goals of INN-BALANCE.

The EU funded research and innovation project focuses on the Balance of Plant components, developing new features for the supply of hydrogen and air to the stack and improved concepts for the thermal management and advanced control architecture of the fuel cell system.

Project duration: 01/2017–10/2021
Participant countries: Austria, Germany, Spain, Sweden and Switzerland

INN-BALANCE guidebook

The present guidebook presents the main project activities and the main results generated by the nine partners of INN-BALANCE. It also contains an overview of the current market for hydrogen vehicles in Europe and provides an outlook to future challenges in this field. The main target groups of this document are vehicles OEMs and their suppliers, fuel cell integrators and manufacturers, BoP manufacturers, research institutions, public authorities such as municipalities and policy makers and other stakeholders from the fuel cell, automotive, energy and transport sectors such as utilities, clusters / networks.

1 Introduction to INN-BALANCE

1.1 Project rationale

Alternative fuels are expected to be a game changer in the fight against climate change and global warming. Hydrogen when produced from renewable energy sources can be used in several applications including the transport sector and contributes to reduce the emissions of greenhouse gases caused by conventional cars powered by internal combustion engines (ICE). To achieve a successful market deployment of hydrogen technologies in Europe, four main conditions need to be met: 1. An European wide hydrogen production and distribution infrastructure should be implemented; 2. The reliability and interoperability of hydrogen-based components and systems should be improved; 3. Significant cost-reductions are required to make hydrogen applications competitive with conventional solutions, which will in turn contribute to sustain high investor confidence and to reach a broader consumer base; and 4. Awareness should be raised on the importance of hydrogen technologies to cope with climate related challenges and a supportive legal framework should be set up, such as the EU Green Deal, supporting the development and market uptake of hydrogen solutions.

The INN-BALANCE project addresses the last 3 challenges listed above. The objective of INN-BALANCE is to develop advanced balance-of-plant components (BoP) for current generation of fuel cell-based vehicles. INN-BALANCE aims at improving the efficiency and reliability of BoP components, reduce their costs to make them ready for mass manufacturing and commercialisation to European automotive manufacturers and system integrators. The project also focuses on the development of training materials and the dissemination of project results to professionals from the hydrogen sector, as well as to the general public, in order to foster the future exploitation of results and support the public acceptance of this relative novel technology. The technical objectives of INN-BALANCE are 1. to develop highly efficient and reliable fuel cell BoP components; 2. to reduce the cost of current market products in fuel cell systems; 3. to achieve a high Technology Readiness Level (TRL 7 or higher) in all developments addressed; and 4. to improve and adapt development tools for design, modelling and testing of innovative components in fuel cell-based vehicles.

1.2 Balance of Plant (BoP) components

All components of a fuel cell system, excluding the fuel cell stack which converts hydrogen into electricity, are referred to as Balance of Plants components. These components ensure that the fuel cell stack runs smoothly and help detect failures at an early stage or even predict them before they occur. Balance of Plant components include compressors, pumps, sensors, heat exchangers, humidifier, recirculation blowers, etc. In INN-BALANCE, different modules consisting of several components were defined, based on the function and service they provide:

- The cathode module which supplies a desired mass flow of air at a particular reference humidity to the FC stack,
- The anode module which provides the required amount of hydrogen to the fuel cell stack and recirculates unused hydrogen to increase the hydrogen utilization rate of the FC stack,
- The control system which ensures smooth running and prevents and eliminates any source of disturbance that may hamper the functioning of the system,
- The thermal management system keeps all components of the fuel cell system at a desired temperature and enables successful cold starts of the FC system.

1.3 Consortium

The INN-BALANCE consortium is composed of a well-balanced group of key Industrial actors (BRO, AVL, CEVT, AYE), research and technology organizations (DLR, S2i), SMEs with research capabilities (CEL, PCS) and a higher research institution (UPC). The INN-BALANCE partners represent 5 countries: Spain, Germany, Sweden, Austria and Switzerland.

The background / knowledge brought by partners is as follows:

Short name	Full name	Background and specific skill of the company
AYE (Spain)	Fundación AYESA	Manufacturing-oriented design optimization and supply chain modelling.
BRO (Germany)	Brose Fahrzeugteile SE & Co. Kommanditgesellschaft, Würzburg	Cathode module design, turbo compressor manufacturing-oriented design, turbocompressor and cathode module testing in hardware in the loop (HIL) and accelerated tests.
AVL (Austria)	AVL List GmbH	Diagnostic system of the state of health for the fuel cell stack. Automotive control systems and anode module technology.
CEVT (Sweden)	China Euro Vehicle Technology AB	Automotive standards and requirements. Integration of the fuel cell system in the powertrain of a vehicle. Testing of the fuel cell system under automotive conditions.
PCS (Sweden)	Powercell Sweden AB	Optimized layout, testing of performance, functionality, assembly and manufacturing of fuel cell stacks.
UPC (Spain)	Universitat Politecnica de Catalunya	Prognosis models, advanced control algorithms, lifetime system evaluation.
DLR (Germany)	Deutsches Zentrum für Luft- und Raumfahrt e. V.	Thermal management design and anti-freeze module design.
S2i (Germany)	Steinbeis 2i GmbH	Dissemination and exploitation of results and expertise in technology transfer.
CEL (Switzerland)	Celeroton AG	High-speed turbo-compressor technology.

Table 1: Overview of the INN-BALANCE consortium.

1.4 Objectives of INN-BALANCE

The objectives of INN-BALANCE are as follows:

Definition of automotive requirements and system architecture

Define the automotive system specifications of BoP components of a 100 kW PEM fuel cell and develop a standardized system architecture and models to scale up and improve the fuel cell system layout.

Development of a dynamic control-oriented model and advanced control system of the FC stack

Develop a dynamic control-oriented model of the complete fuel cell system and innovative diagnosis system, as well as advance control strategies to increase the fuel cell system efficiency and lifetime.

Design and development of cathode module and anode module

Design and develop an innovative cathode module based on a new air turbo-compressor and a novel anode module with greater H2 injection and recirculation capabilities. A cost-effective manufacturing-oriented approach will be followed to decrease the costs and make the modules ready for mass production.

Design and development of thermal module with innovative cold start capabilities

Develop a highly efficient thermal management system featuring an innovative cold start procedure allowing for cold start without fuel cell degradation effects which may be caused by icing.

Commissioning, testing and evaluation of the FC system

Integrate, test, and evaluate all BoP components together with a fuel cell stack in a test bench and adapt and integrate the complete fuel cell system for its final integration and testing in a vehicle powertrain to carry out the final assessment under real driving conditions.

Dissemination and exploitation of results

Elaborate an exploitation strategy supporting the successful exploitation of results produced within the project.

1.5 Current market for H2 fuel cell vehicles in Europe (as of mid-2021)

The following section presents key figures and facts regarding the current market for FC vehicles in Europe. This background information allows to have a better understanding of the market situation and the major developments to be expected in the coming years.

Registered Fuel Cell Electric Vehicles in Europe

Germany and France are by far the countries with the most registered FCEVs in Europe with respectively 808 and 658 registered vehicles. In Germany, most registered vehicles (91%) are passenger cars (category M1) while in France, the share of light commercial vehicles (category N1) represent 41% of all registered FC vehicles (273 out of 658). 5 countries follow in the ranking with more than 100 registered FC vehicles: The Netherlands, United Kingdom, Norway, Switzerland, and Denmark.

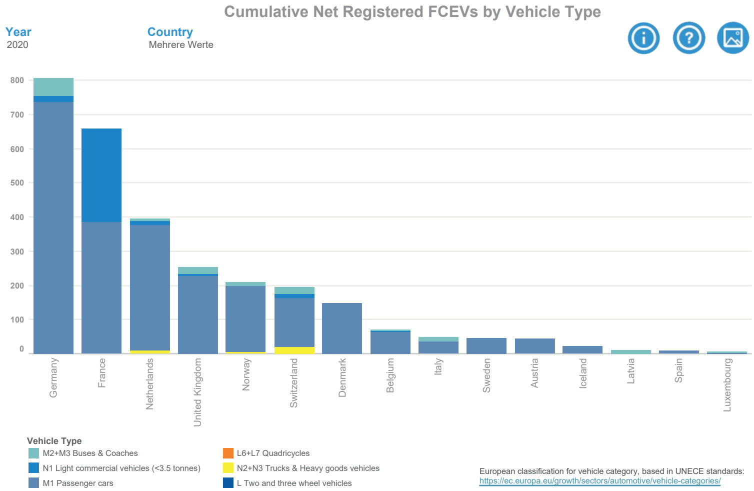


Figure 1: Registered FCEVs in Europe (2008–2020), Source: FCH observatory based on data from the European Alternative Fuels Observatory [FCH Observatory 2021].

Hydrogen refuelling stations deployed in Europe

At the end of 2020, 553 hydrogen refuelling stations were in operation worldwide. Europe has a total of 200 stations, 100 of which are in Germany. France is second in Europe with 34 stations in operations and 38 being currently planned. While most of the European stations are dedicated to the fuelling of passenger cars, the French stations aim primarily at the refuelling of buses and commercial vehicle fleets. This is also reflected in the high number of FC based vehicles carrying goods registered in France. The Netherlands experiences a strong growth with 23 planned stations [Ludwig-Bolkow-Systemtechnik 2021]. An interactive map of all H2 stations can be viewed online at following link: https://www.h2stations.org.

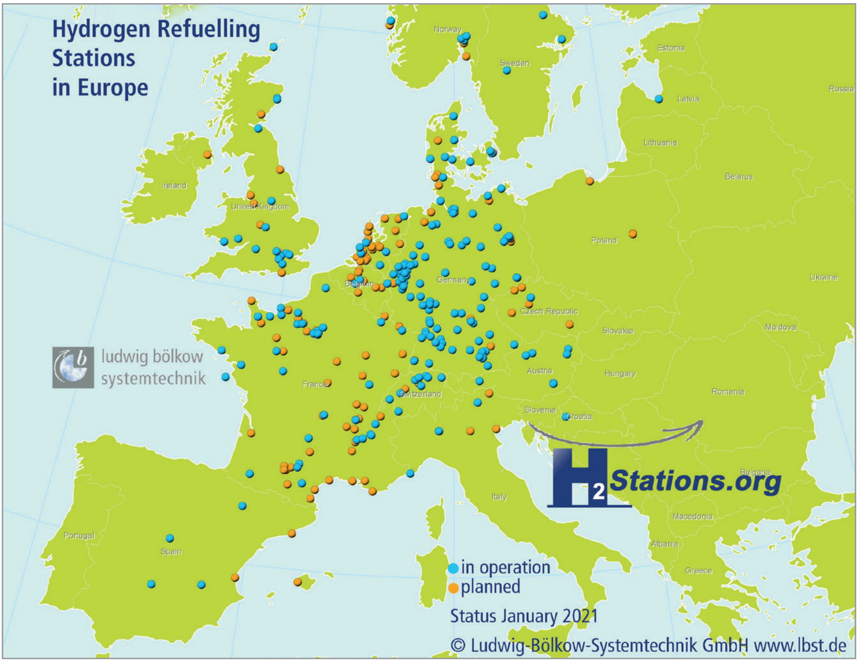


Figure 2: Hydrogen refuelling stations in Europe, Source: h2stations.org by Ludwig-Bölkow-Systemtechnik [Ludwig-Bölkow-Systemtechnik 2021].

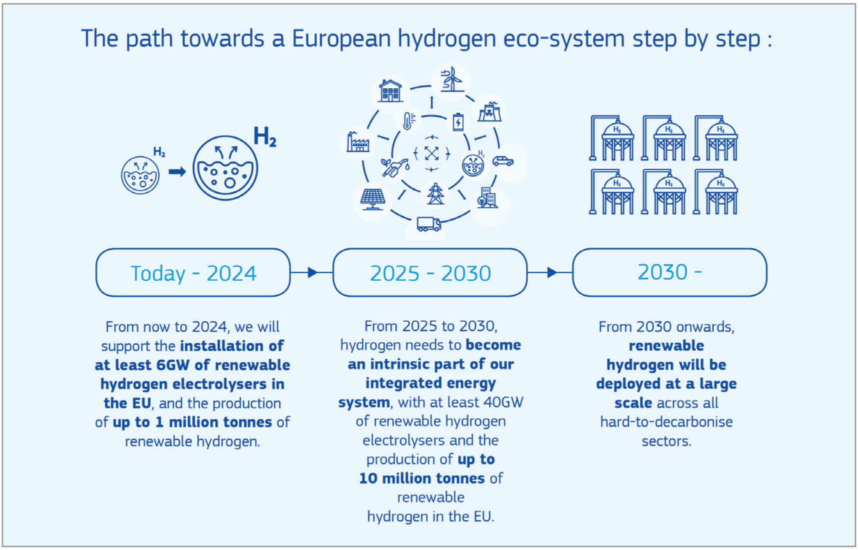
EU political commitment for a global hydrogen strategy

The registration of FCEV vehicles and the deployment of hydrogen refuelling stations must go hand in hand with the production of low carbon hydrogen in Europe. The European Commission published on July 8th, 2020 its hydrogen strategy until 2050 for a climate-neutral Europe with a strong focus on the development of renewable hydrogen and an European hydrogen ecosystem [European Commission 2020a]. This is to be done in different phases:

1. In the first phase (2020–2024), the primary goal is to install at least 6 GW of electrolysers in the EU and reach a production of up to 1 million tons of renewable hydrogen. During this phase, the manufacturing of electrolysers needs to be scaled up and some of the existing H2 production plants need to be decarbonized with carbon capture and storage (CCS) technologies.

The first electrolysers could be installed next to refineries, steel plants and chemical industrial areas. Hydrogen refueling stations are expected to later boost the uptake of fuel-cell buses and trucks. The regulatory framework will be further adapted to incentivize the supply and demand market and push for large wind and solar power plants dedicated to hydrogen production.

2. In the second phase (2025–2030), renewable hydrogen production is assumed to be cost-competitive with other ways of production and other applications and markets will be addressed, such as the steel-making industry, heavy duty and maritime transport. Hydrogen might also be used to balance fluctuating renewable power plants and to help relieve stress on the power grid. At least 40 GW of renewable electrolysers should be installed by 2030 leading to a production of 10 million tons in the EU. Local hydrogen valleys and regions are expected to play an increasing role by then. A strong EU support will be needed to stimulate investments and build a pan-European network of fueling stations and a logistical infrastructure for hydrogen transport.
3. During the third phase (from 2030 onwards until 2050), technologies should reach maturity and be deployed EU-wide to contribute to the decarbonization of all sectors from aviation to shipping to industrial and commercial buildings. According to the hydrogen strategy formulated by the European Commission, it is estimated that a quarter of renewable electricity might be used for hydrogen production by 2050. Biogas might also be used to replace natural gas in hydrogen production facilities given that CO2 emissions are avoided.


The path towards a European hydrogen eco-system step by step :

Today - 2024

From now to 2024, we will support the **installation of at least 6GW of renewable hydrogen electrolysers in the EU**, and the production of **up to 1 million tonnes** of renewable hydrogen.

2025 - 2030

From 2025 to 2030, hydrogen needs to **become an intrinsic part of our integrated energy system**, with at least 40GW of renewable hydrogen electrolysers and the production of **up to 10 million tonnes** of renewable hydrogen in the EU.

2030 -

From 2030 onwards, **renewable hydrogen will be deployed at a large scale** across all hard-to-decarbonise sectors.

Figure 3: The pathway towards an European hydrogen infrastructure and economy, Source: European Commission [European Commission 2020c].

This strong European political commitment is a prerequisite for the market uptake of FC vehicles and the associated refuelling infrastructure. As presented in the next sections, the INN-BALANCE innovations can support this hydrogen transition, by significantly improving the efficiency and reliability of FC vehicles while reducing the manufacturing costs of BoP components.

2 Core project activities

INN-BALANCE applies a linear design and validation methodology depicted below with the objective of achieving a high TRL by project end (TRL 7 or higher) and pave the way for the commercialisation of the BoP components. In parallel to the improvement and technical validation of the modules of the fuel cell-based vehicle powertrain, a specific task focusing on manufacturing-oriented design is carried out to pave the way for the mass production of the novel improved components.

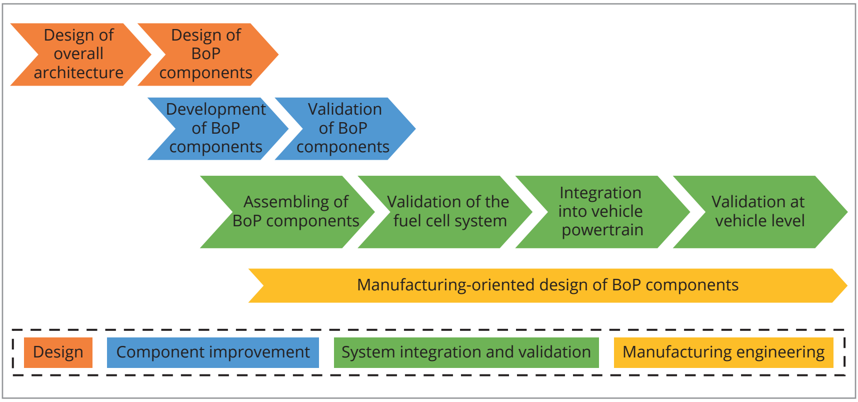


Figure 4: INN-BALANCE design and validation methodology, Source: INN-BALANCE Project.

2.1 Architecture and system level optimization and design

During the first year of the project, project partners worked on the overall architecture of the complete FC system and on the design of the novel BoP components. A new and improved architecture to fit an electrical power system of 80–120 kW was developed and automotive technical requirements were considered by performing packaging and NVH simulation. Under this task, the layout, requirements and interfaces (inlets and outlets for hydrogen, coolant and air) of the 5 main subsystems of the fuel cell system were defined: the cathode module, the anode module, the thermal management system, the fuel cell stack and the fuel cell control unit.

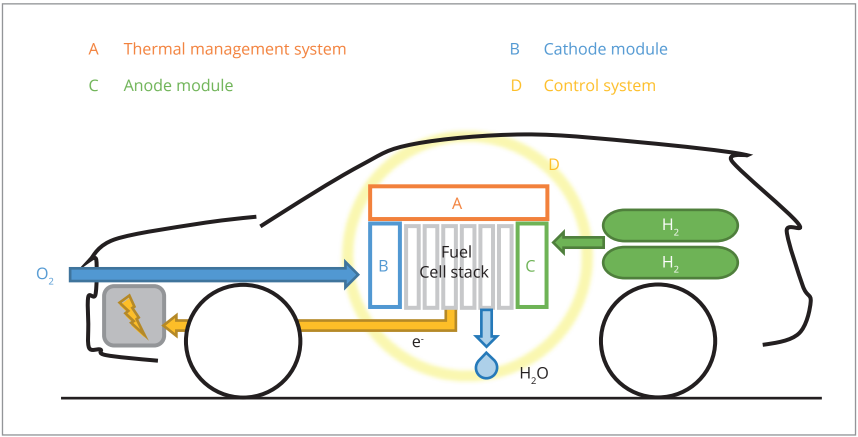


Figure 5: Overall simplified architecture of INN-BALANCE's automotive fuel cell systems, Source: INN-BALANCE Project.

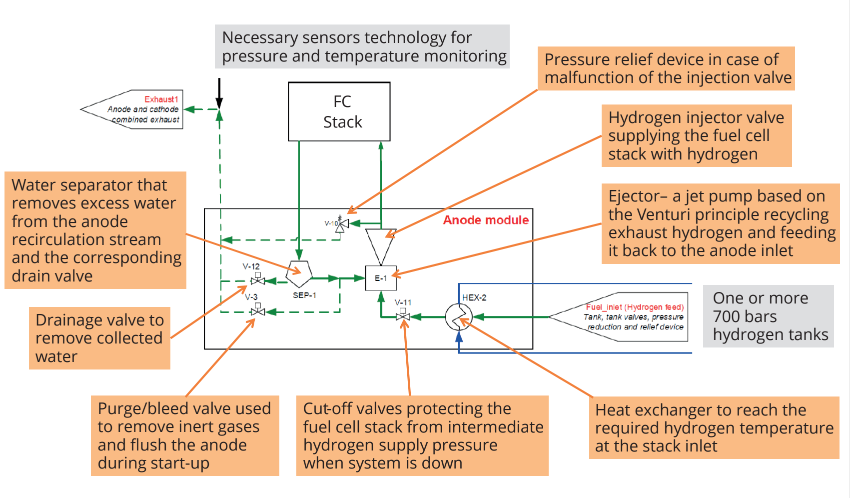
The picture above shows the overall architecture of the fuel cell system. The cathode model purifies and supplies air to the fuel cell stack, while the anode module provides the required amount of hydrogen. The electricity generated by the fuel cell stack is supplied to the powertrain and water is produced as by-product. The thermal management system aims to keep the fuel cell stack at an optimal temperature and allows for a cold start of the stack when outside temperature is below the freezing point. It also manages the temperature of the air and the hydrogen feed. The control system consists of hardware and software components and can be seen as the "brain" of the fuel cell system. It ensures a smooth running of the entire system and tracks and prevents any source of disturbance as early as possible.

2.2 Development of novel BoP components

As outlined in the first paragraph, INN-BALANCE aims at improving the efficiency and reliability of BoP components, developing new features to respond to market and consumers' needs and reducing their costs to make them ready for mass manufacturing and commercialisation to European automotive manufacturers and system integrators. The main improvements to the BoP are detailed in the following sections.

Innovative anode module with passive recirculation system

The anode module supplies a certain amount of hydrogen to the fuel cell stack. To avoid fuel starvation in the stack during operation, an excess of hydrogen is supplied to the stack. The unused hydrogen, which exits the stack has to be recovered and recirculated to increase the hydrogen utilization rate and overall efficiency of the FC system. This recirculation can either be performed actively by the means of a blower, or passively by means of a so-called ejector, a jet pump based on the Venturi principle. The INN-BALANCE consortium decided to develop an improved anode module with a passive recirculation system based on an ejector, allowing for a higher efficiency of the fuel cell system. Since the hydrogen recirculation rate strongly depends on the geometry of the Venturi nozzle, an individual engineering solution had to be specially developed and adapted to the fuel cell stack and available packaging space.



Necessary sensors technology for pressure and temperature monitoring

Pressure relief device in case of malfunction of the injection valve

Hydrogen injector valve supplying the fuel cell stack with hydrogen

Ejector– a jet pump based on the Venturi principle recycling exhaust hydrogen and feeding it back to the anode inlet

One or more 700 bars hydrogen tanks

Water separator that removes excess water from the anode recirculation stream and the corresponding drain valve

Drainage valve to remove collected water

Purge/bleed valve used to remove inert gases and flush the anode during start-up

Cut-off valves protecting the fuel cell stack from intermediate hydrogen supply pressure when system is down

Heat exchanger to reach the required hydrogen temperature at the stack inlet

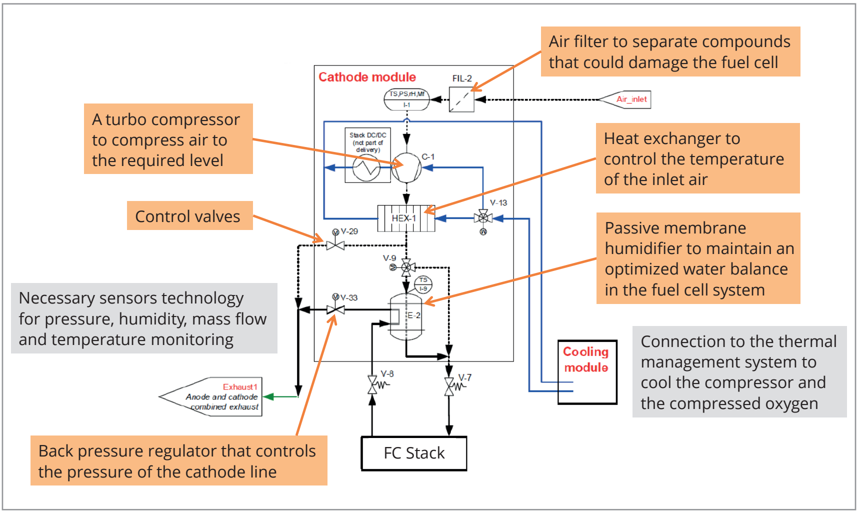
Figure 6: System diagram of the innovative anode module with a passive recirculation system, Source: INN-BALANCE Project.

Main development steps

Partner AVL worked on a first design of the anode module and its components, which was further improved based on the feedback from partner PCS. PCS redesigned the adapter plate of the fuel cell stack to allow for a better integration of the anode components, thus contributing to save space. Further Computational fluid dynamics (CFD) simulations led to fine-tuning of the components and final adjustments of the anode module.

Innovative cathode module with novel turbo-compressor

The cathode module supplies a desired mass of air at a particular reference humidity to the FC stack. To ensure proper functioning of the fuel cell stack, the pressure, mass flow, temperature and humidity of the air to be fed into the stack is constantly monitored. The advanced cathode module of INN-BALANCE consists of an improved turbo-compressor with air-bearing, which compared to conventional oil-bearing guarantees that the air supply remains pure and that pressure fluctuations are greatly reduced and eliminated. The turbo-compressor is also characterized by its high-speed, achieving up to 160 krpm without any noise or vibration, and allowing a dynamic control of both pressure and mass flow. The aerodynamic design of the compressor was developed in such a way to optimize the performance of both stack and compressor in all operating points.



Air filter to separate compounds that could damage the fuel cell

A turbo compressor to compress air to the required level

Heat exchanger to control the temperature of the inlet air

Control valves

Passive membrane humidifier to maintain an optimized water balance in the fuel cell system

Necessary sensors technology for pressure, humidity, mass flow and temperature monitoring

Connection to the thermal management system to cool the compressor and the compressed oxygen

Back pressure regulator that controls the pressure of the cathode line

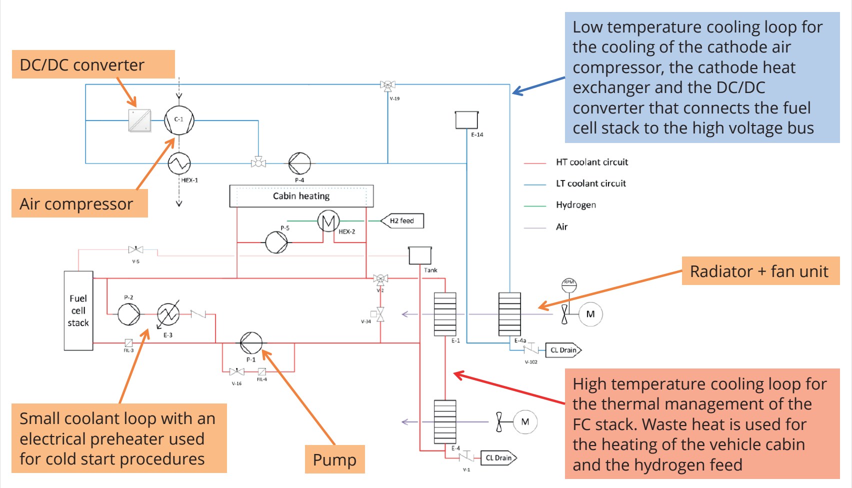
Figure 7: System diagram of the innovative cathode module with its improved turbo-compressor, Source: INN-BALANCE Project.

Main development steps

Partner BRO coordinated the development of the first layout of the cathode module based on inputs from DLR, CEL and PCS. In a second step, partner CEL assembled and tested several prototypes of its turbo-compressors while partner BRO tested and compared various components such as valve sensors, humidifiers and heat exchangers. BRO also developed a control algorithm of the anode module and tested it in a simulation environment. The software was then tested together with the other components under laboratory conditions and various performance tests were carried out. The design of the turbo-compressor was steadily refined by BRO and CEL to ensure easy integration and interoperability and improve the manufacturing process of the compressor. Further fine-tunings were made once the cathode subsystem was assembled and tested as part of the complete automotive fuel-cell system.

Thermal management system featuring a novel cold start procedure

The thermal management system keeps all components of the fuel cell systems at a desired temperature level. In normal operation, it removes excess heat from the fuel cell stack, the fuel cell DC / DC converter as well as from the compressor and its associated electronics. In addition, the thermal system interacts with the cathode and anode modules: it cools the compressed air before it enters the humidifiers and heats the hydrogen to the operating temperature of the fuel cell stack. There are two main temperature loops: a low temperature loop and a high temperature loop (see figure below for additional information). The main innovation of the thermal management systems is its novel cold start procedure that prevents ice formation in the fuel cell stack. This allows to cold start the fuel stack safely when temperatures are below zero (under –30 °C under laboratory conditions) and protects the fuel cell stack from permanent damages.



DC/DC converter

Air compressor

Low temperature cooling loop for the cooling of the cathode air compressor, the cathode heat exchanger and the DC/DC converter that connects the fuel cell stack to the high voltage bus

Radiator + fan unit

High temperature cooling loop for the thermal management of the FC stack. Waste heat is used for the heating of the vehicle cabin and the hydrogen feed

Small coolant loop with an electrical preheater used for cold start procedures

Pump

Figure 8: System diagram of the innovative thermal management system, Source: INN-BALANCE Project.

The operation of the cold start process is explained in the following diagram:

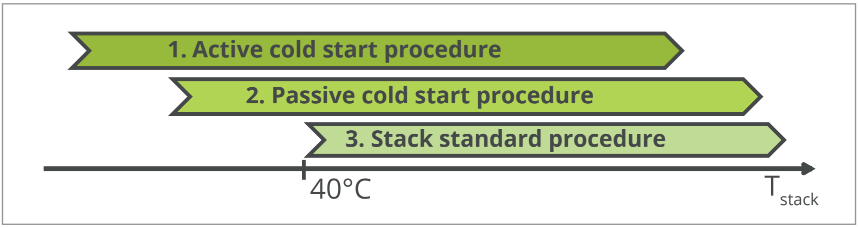


Figure 9: INN-BALANCE cold start procedure, Source: INN-BALANCE Project.

The cold start procedure consists of the following steps:

1. Active cold start procedure: closing of the small cooling loop connecting the input and the output of the fuel cell stack. The coolant will be pumped from the outlet to the inlet with the maximum flow rate and the heater will be switched on to heat the coolant.
2. Passive cold start procedure: The compressor is started at high flow rate while the flow rate of the coolant is reduced at its minimum. Once the stack reaches sufficient operation temperature, the coolant flow is smoothly shifted from the small loop to the main loop.
3. Stack standard operation: stack standard operation when stack temperature is above 40 °C.

Shutdown procedure: a cathode purge is performed when the fuel cell system is being shut down and dry gases are flushed into the cells to remove water droplets.

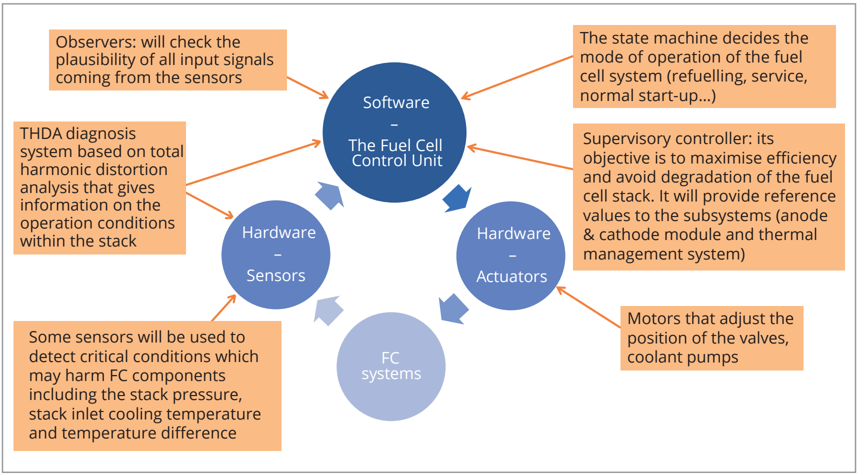
Main development steps

Partner DLR developed the design and concept of the thermal management system as well as the control scheme while partner BRO developed simulation models for the low temperature circuit to minimize the number of system components and optimize its efficiency. The thermal management system was then built and tested under laboratory conditions by partner DLR before its integration in a test bed for validation at system level by partner PCS. A manufactured-oriented redesign of the thermal module was carried out by BRO to improve the later integration into the fuel cell system.

Besides these activities, DLR also tested as part of INN-BALANCE an alternative cold storage procedure based on the injection of an anti-freeze fluid such as methanol into the fuel cell stack. This novel approach should enable cold storage of the fuel cell at temperatures down to –40 °C without ice formation. This eliminates any degradation that could occur during conventional cold storage and enables cold start-ups at lower temperature procedures. Partner DLR published articles and participated in conferences to present this disruptive method [Knorr et al. 2019], [Montaner et al. 2020a], [Montaner et al. 2020b].

Enhanced fuel cell control system

The fuel cell control system ensures the smooth running of the fuel cell system and precisely monitors the main parameters of the fuel cell system to identify significant changes indicative of a developing fault. It also optimizes the fuel cell system performance in every operating mode and communicates and interacts with the vehicle control system which controls all other equipment and sensors other than those related to the hydrogen system. The control system consists of sensors, software modules and actuators which respectively measure the main parameters of the fuel cell system, decide the mode of operation based on the inputs collected from the sensors and the algorithm of the controller, and send commands and set points to pumps, valves and servomotors to adjust the system operation according to the strategy set by the controller. The basic operation of the fuel cell control system is depicted below.



Observers: will check the plausibility of all input signals coming from the sensors

THDA diagnosis system based on total harmonic distortion analysis that gives information on the operation conditions within the stack

Some sensors will be used to detect critical conditions which may harm FC components including the stack pressure, stack inlet cooling temperature and temperature difference

The state machine decides the mode of operation of the fuel cell system (refuelling, service, normal start-up…)

Supervisory controller: its objective is to maximise efficiency and avoid degradation of the fuel cell stack. It will provide reference values to the subsystems (anode & cathode module and thermal management system)

Motors that adjust the position of the valves, coolant pumps

Figure 10: Main components of the fuel control system and their interactions, Source: INN-BALANCE Project.

One of the main innovations of the INN-BALANCE control system is the implementation of a total harmonic distortion analysis (THDA) device developed by partner AVL, which is a novel non-intrusive method to monitor the operating conditions of the fuel cell stack. Compared to conventional solutions such as cell monitoring, THDA allows to save space, increase the reliability of the fuel cell system by predicting and identifying harmful conditions and early cell degradations that could lead to irreversible damages.

Main development steps

Partner UPC coordinated the development of an integrated simulation model consisting of subsystems of the fuel cell system. Partners AVL, DLR and BRO provided inputs and contributed to the development of this model. It was used to simulate and control the FC system in different operating modes. Partner UPC also led the development of control strategies based on technical requirement and operating strategies provided by the industrial project partners. In parallel, AVL worked on the development, implementation and testing of the THDA technology. AVL also selected a control unit for the fuel cell system and developed a control architecture which integrates all software components. The validation of the control system was performed by partner PCS and CEVT after the assembling and commissioning of the fuel cell system (see next section).

2.3 System integration, testing and evaluation

The system integration activities started with the construction of a test rig by CEVT. This testbed, which can accommodate all INN-BALANCE components, was later shipped to partner PCS. To ensure safe operation and assess the functionality of the entire system, partner PCS conducted a sequential testing of the different subsystems in its testing facilities in Sweden. The commissioning of the INN-BALANCE fuel cell system started in mid-2020 but was delayed due to technical issues and missing components due to transport restrictions caused by the COVID19 virus outbreak.

Figure 11:
PCS receives the fuel cell test rig from CEVT in September 2020, Source: Powercell Sweden AB.

One of the main challenges faced during the commissioning of the fuel cell system was interoperability issues encountered when assembling the different hardware and software modules. Some adaptations were necessary to ensure that the various components and software perform their tasks appropriately, according to the technical specifications defined at project start. This commissioning was supported by all partners responsible for the development of the different modules and components of the fuel-cell system. Compared to the initial plan, which envisaged that the partners would travel to support the commissioning on site, most of the support was provided online.

Once the tests at PCS were concluded, the fuel cell system was sent back to CEVT and implemented in the vehicle powertrain (see figure below). The fuel cell powered vehicle then underwent a commissioning process where the high voltage system and the hydrogen system carefully was taken into operation. Once the vehicle was considered OK to undergo testing it was installed in a vehicle rig at Chalmers University of Technology, where calibration and optimization of the FC system continued together with Chalmers, PCS and AVL.

This was followed by several vehicle rig tests: the vehicle performance was assessed under different drive cycles, with high focus on WLTC and energy consumption and the high voltage system and hydrogen system of the vehicle were inspected during the vehicle's normal operation. Furthermore, the FCEV underwent testing during real driving conditions at CEVT Proving Ground, where performance and functionality was tested, as well as environmental aspects during a Cold Start Campaign written by DLR. Partner PCS and CEVT, with the support of all other partners participating in the testing activities, carefully recorded all results and findings from the system integration and testing activities and integrated them into a final evaluation report.

Figure 12: Fuel cell system implemented in the vehicle powertrain, Source: China Euro Vehicle Technology AB.

2.4 Manufacturing and cost optimization

The objective of the manufacturing and cost optimisation activities is to identify cost reduction potentials in the manufacturing process of the different INN-BALANCE modules, along the supply chain and during the operation of the different systems. These activities were coordinated by partner AYE and supported by all partners in charge of the development of the sub-modules. An important part of the cost reduction is linked to the manufacturing process: a large part of total cost of manufacturing of a product (cost of materials and costs of manufacturing and assembly) is driven by design choices (number of components / parts, layout of the system, number of assembling steps and assembly simplicity) and only a small portion of the total cost are linked to manufacturing tools and techniques. Some studies [Poli 2001] argue that design decisions account for more than 70 % of total product lifetime costs, but this figure is contested by other studies [Barton 2001]. The partners responsible for the improvement of the different INN-BALANCE modules identified optimisation potential regarding overall performance and cost-effectiveness. It could be observed that some components can be optimized individually but further research is required to test and validate new module designs and manufacturing concepts, in order to bring cost of series production to a competitive level.

Partner AYE also developed an optimization framework, a simulation software which allows to identify and quantify cost reduction potential in a systematic way, for various manufactured systems of a fuel cell-based system. This tool is divided into 3 modules: a manufacturing module which allows to select materials and manufacturing processes for each manufactured part, a supply chain module which enables the user of the tool to define parameters such as stock and transport of raw materials required for the manufactured device and to assess the corresponding costs, and a performance module that analyses and assesses the performance of selected devices, such as valves and sensors, and allows to compare the costs and performance of several options to identify the best one. This optimization software runs on MATLAB-Simulink® environment and is based on data and information provided by project partners. Several tests and simulations were performed to validate the results.

3 Project results: improved INN-BALANCE components and procedures

The following sub-sections present the main results of the INN-BALANCE projects for each of the main research areas addressed by the project.

3.1 Anode module

3.1.1 Control strategy of the anode module of the FC stack

Name (partner owning the innovation)

Control strategy of the anode module of the FC stack (AVL)

Description / main functions

An improved control strategy for the anode module of automotive fuel cell system, which oversees all components of the anode module was developed.

The verification of the anode module concept was performed in several steps. First an injector testbed was built at AVL facilities to validate the function of the new design. In the next step the anode module was mounted on the stack for the fuel cell system operation.

In the picture below an example of the anode pressure control is shown. The anode pressure (red) is controlled to follow the cathode pressure, which is again a function of the stack current (blue). The brown curve shows the differential pressure of anode and cathode.

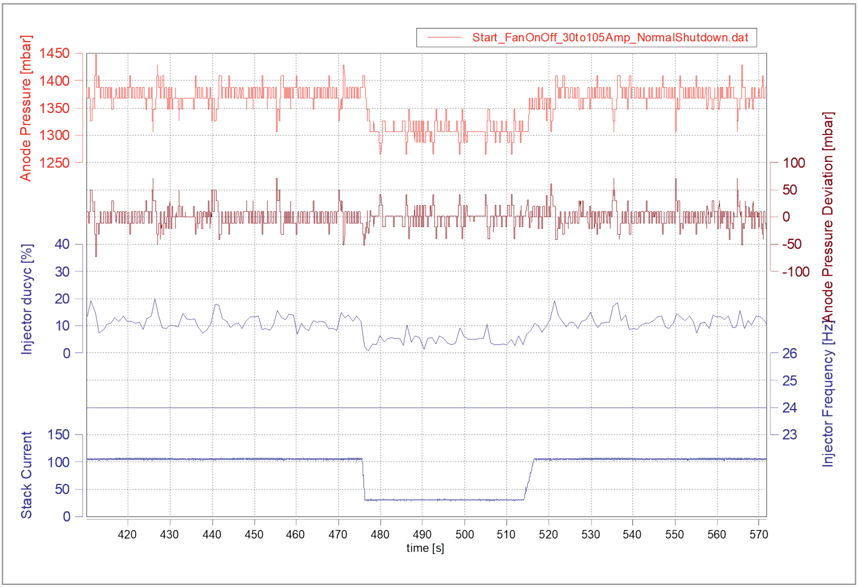
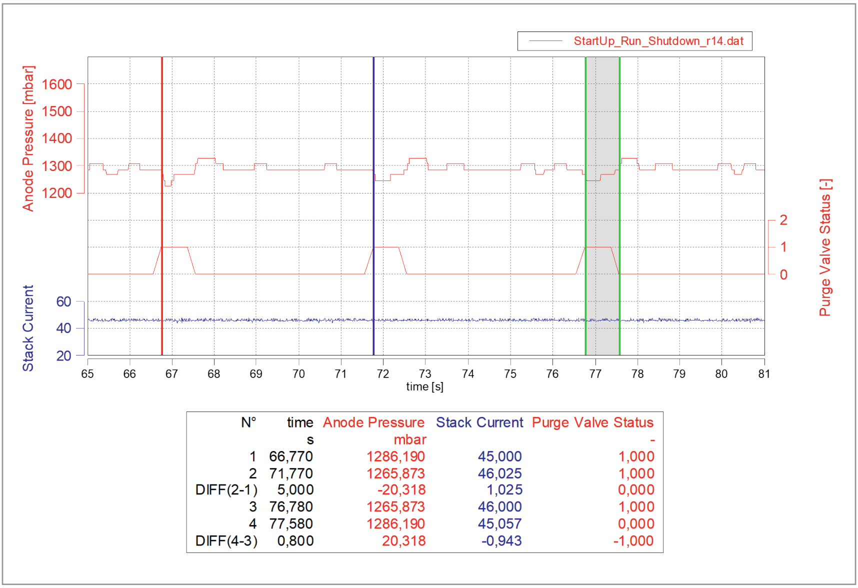


Figure 13: Anode module control by AVL strategy (anode pressure control), Source: AVL List GmbH.

The control of the anode module also contains the anode purge and drain strategy. In the following diagram the purge operations for a certain operation point are shown. Stack current is constant (blue), which leads to a constant purge interval (red), with minor impact on the anode pressure (red).



N°	time	Anode Pressure	Stack Current	Purge Valve Status
	s	mbar		-
1	66,770	1286,190	45,000	1,000
2	71,770	1265,873	46,025	1,000
DIFF(2-1)	5,000	-20,318	1,025	0,000
3	76,780	1265,873	46,000	1,000
4	77,580	1286,190	45,057	0,000
DIFF(4-3)	0,800	20,318	-0,943	-1,000

Figure 14: Anode module control by AVL strategy (anode purge control), Source: AVL List GmbH.

Components

- Injector / ejector system
- Purge valve
- Water separator, water tank and drain valve
- Pressure and temperature sensors

Advantages and innovations

The product improvement is achieved by reducing the number of components and using a model-based gas management that allows to reduce fuel consumption and increase the overall efficiency of the fuel cell system.

Stage of development after INN-BALANCE project (Technology readiness level)

TRL 6–7 – Technology demonstrated in relevant environment

Potential applications (other than FC automotive)

Commercial vehicles, marine applications, stationary fuel cell applications

3.1.2 Optimized ejector for automotive FC stack

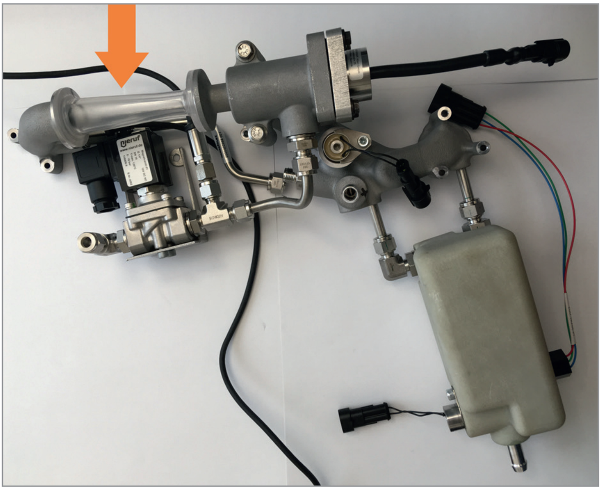
Name (partner owning the innovation)

Optimized ejector for automotive FC stack (AVL)

Description / main functions

An optimized ejector module for automotive FC stack, which contributes to the recirculation of hydrogen in the FC stack was developed.

In the picture below, the complete anode module is shown and the arrow is pointing towards the ejector. It was designed and further optimized in several iterations using AVL simulation tools. The main requirement was the performance of the passive hydrogen recirculation at very low as well as at high loads. Testbed results verified the performance of this passive anode recirculation with an optimized ejector.



Components

- Injector / ejector system
- Purge valve
- Water separator, water tank and drain valve
- Pressure and temperature sensors

Advantages and innovations

The novel ejector is based on a Computational Fluid Dynamics (CFD) design, that leads to a better fuel supply and hydrogen recirculation as well as reduced parasitic losses, allowing for reduced fuel consumption and thus higher overall fuel cell system efficiency.

Stage of development after INN-BALANCE project (Technology readiness level)

TRL 6 – Technology demonstrated in relevant environment

Potential applications (other than FC automotive)

Commercial vehicles, marine applications, stationary fuel cell applications and gas engines

3.2 Cathode module

3.2.1 High speed air compressor for automotive FC

Name (partner owning the innovation)

High speed air compressor for automotive FC (CEL)

Description / main functions

A novel high-speed air compressor with gas bearing (oil free) and its associated electronics for air supply to a 100 kW FC stack.

Figure 16: High speed air compressor and associated electronics from CEL, Source: Celeroton AG.

Components

- Compressor
- Associated electronics

Advantages and innovations

The high-speed turbo compressor is characterized by oil-free air supply, long lifetime, low weight, and high operating efficiency. Its high operation speeds make it suitable for various operating conditions and applications.

Stage of development after INN-BALANCE project (Technology readiness level)

TRL 6–7 – Technology demonstrated in relevant environment

Potential applications (other than FC automotive)

The compressor can be used in various applications which need pressurized and clean air supply.

3.2.2 Optimized cathode module for automotive FC stack

Name (partner owning the innovation)

Optimized cathode module for automotive FC stack (CEL and BRO)

Description / main functions

An optimized cathode module fitted with a high-speed air compressor and benefiting from further improvements of the overall cathode system.

Components

High speed air compressor

Advantages and innovations

The optimized cathode module ensures a higher durability and improved start-up and shut down procedures.

Stage of development after INN-BALANCE project (Technology readiness level)

TRL 7 – System prototype demonstration in operational environment

Potential applications (other than FC automotive)

The improved cathode module could also be suited for stationary FC applications and the heavy-duty vehicles market.

3.3 Thermal management system

3.3.1 Anti-freeze module for automotive FC

Name (partner owning the innovation)

Anti-freeze module for automotive FC (DLR)

Description / main functions

An anti-freeze module for automotive fuel cell system based on a methanol solution that avoids ice formation during cold storage at temperatures down to –40 °C, enabling cold start from even lower temperature than current cold storage solutions. Thus, enlarging the lifetime of the fuel cell and allowing for an extended operating range of the FC vehicle.

The anti-freeze cold storage method was tested with a 5x5cm² single cell and a water-methanol solution (40 % vol.) for more than 80 F / T cycles between –10 °C and +20 °C. As the figure below shows, the use of the anti-freeze solution during freeze-thaw cycling strongly reduces performance degradation as compared to freeze-thaw cycling tests without using anti-freeze or conditioning by purging the cell with dry gases before freezing. Specifically, performance degradation up to current densities of 1.4 A / cm² (peak performance) is fully eliminated by the anti-freeze [Knorr et al. 2019].

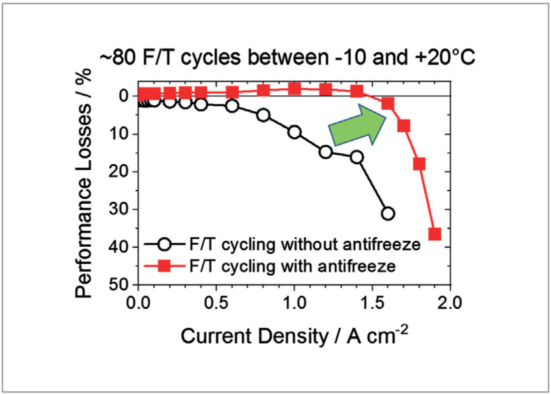


Figure 17:
Performance losses after ca. 80 F / T cycles between –10 °C / 20 °C with and without using antifreeze,
Source: Deutsches Zentrum für Luft- und Raumfahrt e. V. [Knorr et al. 2019].

The cold start ability of a PEMFC system at –10 °C using the anti-freeze module (a methanol concentration of 25 vol %) was tested with a 4 KW degraded stack. Tests results with the stack, same as the cell results, show that flooding the stack with a methanol solution doesn't degrade the stack performance. As the anti-freeze avoids ice formation during the cold storage, several cold starts at –10 °C were carried out with different start-up procedures and operating parameters, all of them successfully. These results were presented at the International Meeting of Electrochemical Society PRiME 2020 [Montaner20_2].

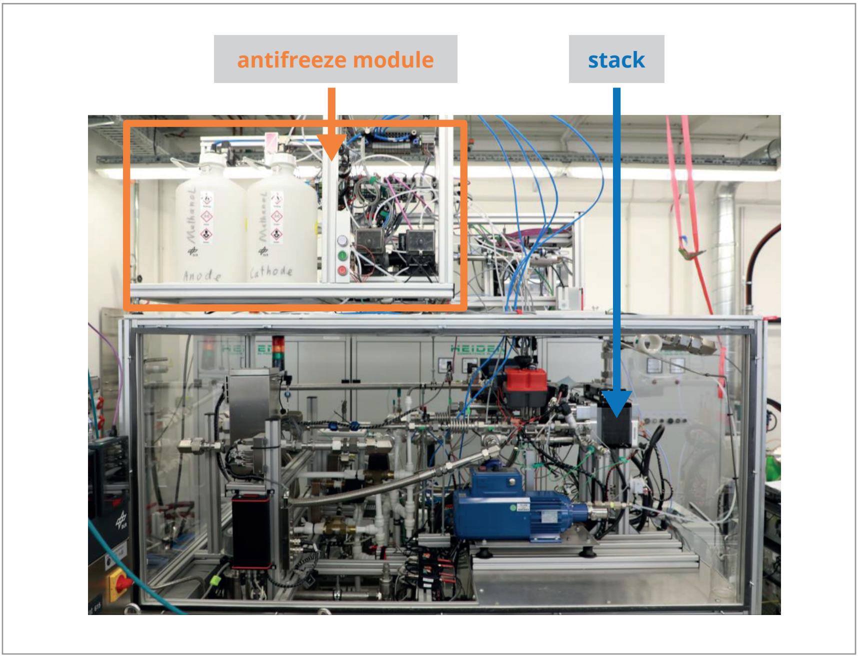


Figure 18: Experimental set up of the anti-freeze module and the stack test bench, Source: Deutsches Zentrum für Luft- und Raumfahrt e. V. [Montaner et al. 2020a].

Components

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Advantages and innovations

The anti-freeze module prevents ice formation during cold storage and reduces the shutdown procedure time, which reduces the risk of FC degradation, improving the lifetime of the fuel cell system. At extreme low temperatures (e. g. –40 °C), the total absence of ice formation cannot be guaranteed with current cold storage solutions, since purging the fuel cell completely would take too long for the automotive requirements.

Stage of development after INN-BALANCE project (Technology readiness level)

TRL 5 – Technology validated in relevant environment

Potential applications (other than FC automotive)

The anti-freeze module is also suited for other applications such as FC based heavy duty vehicles, hydrogen powered rail and maritime transport solutions.

3.3.2 Cooling system for FC powertrain

Name (partner owning the innovation)

Cooling system for FC powertrain (DLR and PCS)

Description / main functions

A novel concept and operation strategy of a FC cooling system leading to a more flexible operation and increased efficiency. The cooling system consists of two separate cooling liquid loops to serve the different temperature levels required. The two loops are operated to provide optimal conditions for stack operation assuring a fast response and minimizing undesired conditions.
The high temperature (HT) cooling circuit is responsible for the cooling of the fuel cell stack. The waste heat of the stack is used for the cabin heating and for the heating of the hydrogen feed. The HT loop also contains a short preheating circuit that provides start-up capability in freezing conditions. A procedure (which also includes the participation of the other subsystems) has been developed and implemented to allow a reliable cold start with no-extra degradation.

The low temperature (LT) circuit is responsible for cooling of the cathode air compressor, the compressor drive including its power electronics, the DC / DC converter and the cathode air intercooler.
Efficient thermal management strategies were developed for cold starts at $T \geq -40\,°C$ of the FCEV by using the LT circuit and the electric heater. Some results of this investigation were presented at the EFC19 conference [Montaner et al. 2019] and published in Applied Energy Journal [Montaner et al. 2020c].

This strategy was tested with a 4 KW PEMFC system at temperatures down to −30 °C. As an example, next figure shows cold start performances at −25 °C of the 4 kW PEMFC system with a passive strategy (pc5), an active strategy (Ac3) and with this developed strategy (pAl), which consists of warming up the stack with the electric heater until low temperatures, such as −15 °C and then switch off the heater immediately and carry out an optimal passive cold start strategy. As the figure shows, this strategy leads to a more efficient thermal management with less ice formation than standard thermal management strategies.

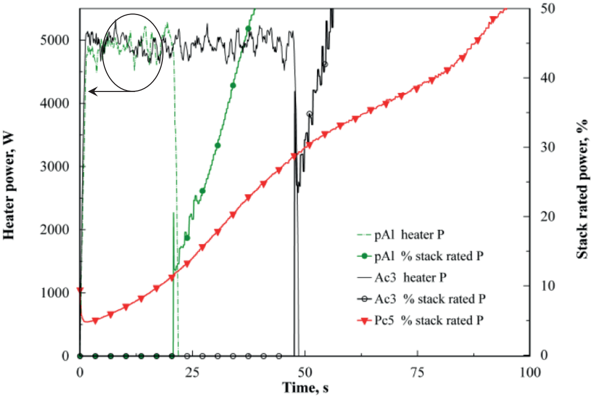

Figure 19: Cold start performance of the stack at −25 °C with different thermal management strategies (passive, active and part active), Source: Deutsches Zentrum für Luft- und Raumfahrt e. V. [Montaner et al. 2020c].

Components

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Advantages and innovations

The novel cooling system allows for improved start-up in freezing conditions and better system response in transient operating conditions, which will contribute to reduce the degradation of the fuel cell system.

Stage of development after INN-BALANCE project (Technology readiness level)

TRL 7 – System prototype demonstration in operational environment

Potential applications (other than FC automotive)

The novel cooling system could also be used in other applications such as off-road vehicles, train, marine and aircraft propulsion.

3.4 Control system

3.4.1 Innovative control system for FC system

Name (partner owning the innovation)

Innovative control system for FC system (AVL and UPC)

Description / main functions

An improved control system based on better models and more precise information on the different states of the fuel cell components was developed.

The control system for the FC system comprises a HW and a SW part. The AVL RPEMS prototype control unit (shown in the picture below) was installed as fuel cell control unit on the testbed and the vehicle as interface between the system and the control SW.

A major part of the development done in the project was the development of the control models, which were integrated into a new developed SW architecture for fuel cell control (see picture below). This includes on the one side of the subsystem controllers (anode, cathode, thermal) as well as an observer and diagnostic part. The core part of the SW was the optimum setpoint generator and supervisor controller, which were developed based on long experience and improved by evaluation of test results.

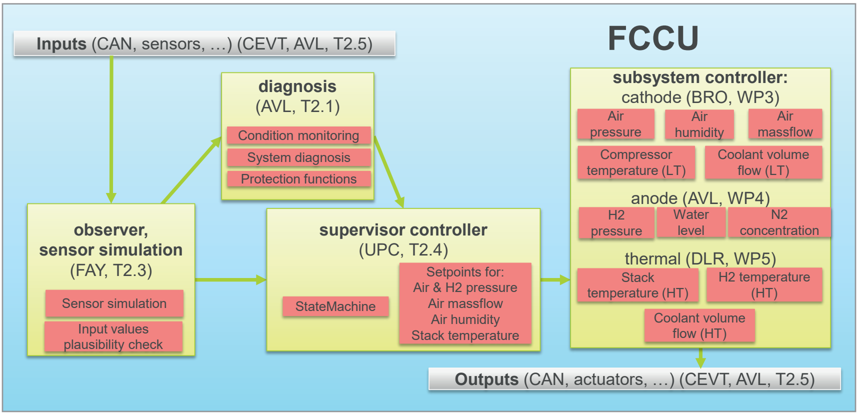

Figure 21: Software architecture of the control system by AVL,
Source: INN-BALANCE project

Components

- Sensors
- Software modules
- Actuators (motors and valves)

Advantages and innovations

The innovative control system ensures longer life and lower operating costs of fuel cell systems through a more precise control unit with accurate estimation of the states of individual fuel cell system components.

Stage of development after INN-BALANCE project (Technology readiness level)

TRL 6 – Technology demonstrated in relevant environment

Potential applications (other than FC automotive)

No other application foreseen for the moment

3.5 FC stack

3.5.1 Compact housing of FC stack

Name (partner owning the innovation)

Compact housing of FC stack (PCS)

Description / main functions

The new housing solution for FC stack ensures safety of the fuel cell stack and guarantees protection from the environment.

Components

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Advantages and innovations

The new compact housing of the FC stack is a new compact off-the-shelf protection for FC stack which increases the overall reliability of the FC system.

Stage of development after INN-BALANCE project (Technology readiness level)

TRL 7 – System prototype demonstration in operational environment

Potential applications (other than FC automotive)

The compact housing is suited for any other FC system with similar environmental requirements

3.5.2 Fuel cell stack POD

Name (partner owning the innovation)

Fuel cell stack POD (PCS and AVL)

Description / main functions

A new stack POD or end plate of the DC stack that allow for a more compact stack and a reduced size since some BoP components and connectors are directly integrated into the stack end plate.

Components

- FC stack end plate
- Gaskets
- BoP components

Advantages and innovations

The new POD stack is a highly space-optimised stack end plate that prevents pressure drops and a high compactness for improved vehicle integration of the FC system.

Stage of development after INN-BALANCE project (Technology readiness level)

TRL 7 – System prototype demonstration in operational environment

Potential applications (other than FC automotive)

The stack POD is suited for any fuel cell applications with restricted space.

3.6 Packaging, assembling, integration into powertrain and test procedures

3.6.1 Packaging, assembling and integration into powertrain

Name (partner owning the innovation)

Packaging, assembling and integration into powertrain (CEVT)

Description / main functions

Packaging, in CAD environment, and physical assembly of all components into test bed as well as into the vehicle.

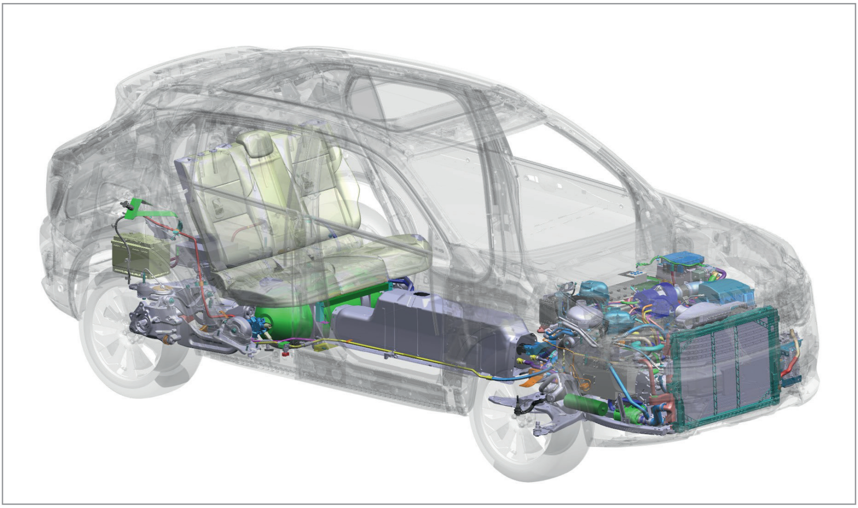

Figure 22: Packaging in CAD environment, Source: China Euro Vehicle Technology AB

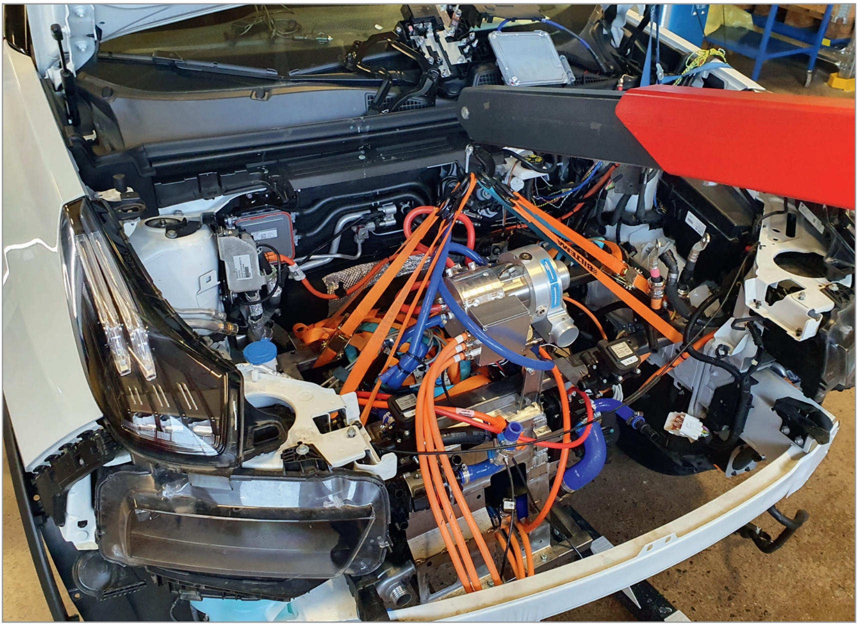

Figure 23: Physical assembly into the vehicle, Source: China Euro Vehicle Technology AB

Components

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Advantages and innovations

The packaging study, assembly and integration is a first big step towards a mass production ready FCEV.

Stage of development after INN-BALANCE project (Technology readiness level)

TRL 5 – Technology validated in relevant environment

Potential applications (other than FC automotive)

The compact packaging is suited for any other FC system with similar environmental requirements

3.6.2 Test procedures for automotive FC system

Name (partner owning the innovation)

Test procedures for automotive FC system (PCS and CEVT)

Description / main functions

Procedures and test methods used for the testing of automotive FC systems to ensure high quality and performance of FC based powertrains and assess the functionality of all components.

Figure 24: CEVT and PCS verifying the vehicle concept and performing the first vehicle tests at, and with support from, Chalmers University of Technology, Source: China Euro Vehicle Technology AB

Components

–

Advantages and innovations

The new test methods and procedures allow to ensure the fuel commissioning of a FC based automotive powertrain through all test cycles: from the commissioning of the FC system after the assembling of all components, to the final integration into a powertrain and the last tests under automotive operating conditions.

Stage of development after INN-BALANCE project (Technology readiness level)

TRL 5 – Technology validated in relevant environment

Potential applications (other than FC automotive)

The developed test procedures can be used for the validation of similar automotive FC systems.

3.7 Optimization of manufacturing process and associated cost reduction

3.7.1 Optimization framework and tool for the analysis of cost reduction potential

Name (partner owning the innovation)

Optimization framework and tool for the analysis of cost reduction potential (AYE)

Description / main functions

An optimization framework has been developed to optimize at the same time all the important parts of the value chains in a concurrent design strategy considering at the same time supply chains, manufacturing and the performance of the system.

Besides, a web-based user interface has been created in order to easily make available to the rest of the consortium partners and the general public the evaluation cost at system, module and component level. This application includes a functionality that can be used to study the economic impact of the optimization framework proposals at system, module and component level.

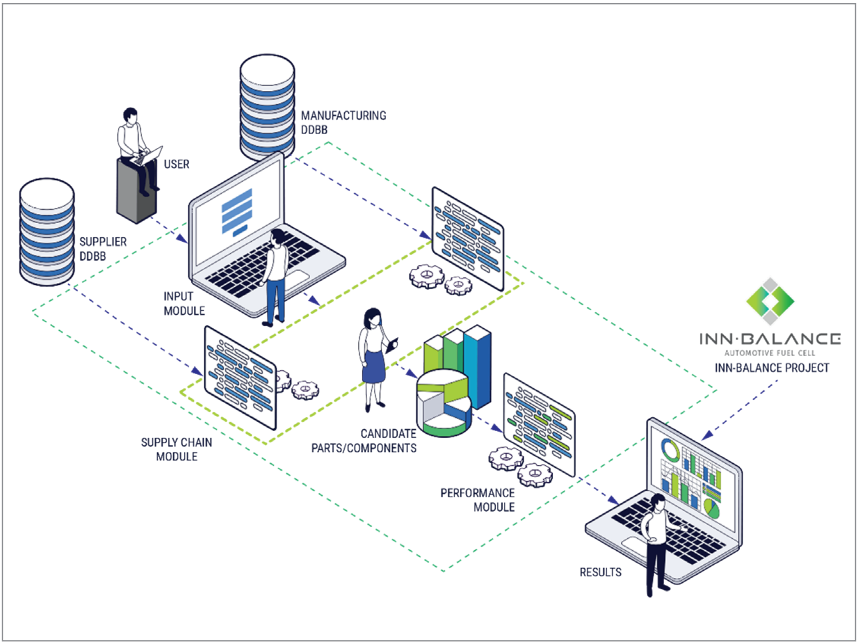

Figure 25: Architecture of the web-based user interface, Source: Fundación AYESA

Components

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Advantages and innovations

This software tool supports the manufacturing process of BoP components and helps designers to choose the best design option and selection of components.

Stage of development after INN-BALANCE project (Technology readiness level)

TRL 6–7 – Technology demonstrated in relevant environment

Potential applications (other than FC automotive)

The tool can be used by developers of BoP components.

4 Conclusions and outlook

The market uptake of FC vehicles depends on several conditions that need to be met. To ensure the future exploitation of INN-BALANCE results, it will be key to leverage the strong political commitment of EU states to hydrogen technologies and make significant efforts to promote greater social acceptance of these technologies, while drastically reducing their cost and adapting the regulatory framework.

4.1 Market outlook: Main drivers and barriers

A strong political commitment of EU member states to hydrogen

The results of a recent study [FCH JU 2020] published in 2020 by the Fuel cells and hydrogen joint undertaking (FCH JU), analysing the national energy and climate plans of the EU member states, shows that several EU countries are considering hydrogen as a key element of their energy transition. Hydrogen is described in many national strategies as an energy carrier and vector with a great potential to decarbonize the EU economy, especially in the field of transport. The authors of this report estimate that the demand for hydrogen and hydrogen applications will continuously grow in the coming years, leading to between 2.5 and 5 million FCEV passenger cars to be deployed in Europe by 2030. It is estimated that 75 % of fuel cell road vehicles (passenger cars, buses, trucks and heavy-duty vehicles) will be rolled out in the large European countries including Germany, Italy, France, the UK and Spain. The percentage of FCEVs as share of total vehicles on the road in 2030 is estimated to vary between 0.5 and 2.5 % in the different member states.

According to the study of the FCH JU [FCH JU 2020], it is estimated that between 4500 and 8100 refuelling stations need to be deployed in the EU28 by 2030 to distribute hydrogen as fuel to road vehicles. The distribution of these stations in the EU countries are determined by the number of FCEVs rolled-out in the different countries. By 2030, between 800 and 1400 hydrogen refuelling stations are expected to be in operation in Germany, between 700 and 1200 in Italy, and between 600 and 1100 in France. In the Netherlands and Poland, the number of stations to be rolled out will be in the range of 100–400. For comparison, 100 refuelling stations in operation corresponds to the number of stations in operation in Germany by early 2021.

Need for more coordination actions, harmonised regulations and an EU-wide infrastructure

Coordination and collaboration at EU level between EU member states is essential to reach the ambitious objectives of the EU Green Deal and EU hydrogen strategy. It will be key to develop and agree on standards, rules and specifications for hydrogen applications to guarantee a high interoperability and the emergence of an EU-wide hydrogen economy. The launch of cross-national hydrogen and energy platforms and initiatives such as Era-Net, increased cooperation between academia and industrial partners in the frame of European research program Horizon Europe and the Fuel Cells and Hydrogen Joint Undertaking, and the adoption of European directives such as 2014 / 94 / EU on the deployment of alternative fuels infrastructure are best practices laying the foundation for an integrated hydrogen energy system. This is particularly relevant for transport-related hydrogen applications which require a common level playing field of practices and policies. Today, transport policies in the EU are characterised by diverging national priorities and this fragmentation will result in untapped potential and lead to interoperability issues between hydrogen solutions [European Commission 2019]. This could negatively impact the market uptake of fuel cell-based vehicles which, in contrast to battery-powered vehicles, have a longer range and are expected to be mainly used for long interregional transport.

Successful hydrogen transition strongly depends on public acceptance

As pointed out in research articles, there is a global lack of understanding about the hydrogen production process and the benefits hydrogen provides. It was also observed that the knowledge on safety of hydrogen production and storage methods is relatively low among the general public [Ingaldi et al. 2020]. This highlights the barriers and difficulties that arise when new technologies such as renewable energy and hydrogen gain momentum. Social resistance may cause delays in market deployment and uptake and may lead in the worst-case scenario to tech failure which could have dramatic consequences for stakeholders of the hydrogen sector and for the achievement of the European climate targets.

Several EU initiatives (EU projects KnoWhy, TeacHy, FCH2EDU) contribute to the capacity building of European citizens on hydrogen technologies. The FCH JU funded project FCHgo aims at fostering knowledge about fuel cell and hydrogen technology by delivering ready-to-teach toolkits to EU teachers. This stimulates pupils' interest and awareness for sustainable energy and teach them about the basic principles and applications of fuel cell and hydrogen-based technologies [FCHgo 2019]. Past projects such as HYACINTH analysed in depth the public awareness of fuel cell technologies by conducting surveys in seven EU countries. The results show that most of the people interviewed have a positive evaluation of FCEVs and respondents generally express a preference for FCEVs over conventional cars provided that the purchase price of the vehicle and the refuelling infrastructure is identical to that of conventional cars [HYACINTH 2017].

Competitiveness of hydrogen fuel price and fuel cell-based system cost as a key success factor

To ensure fast market adoption, FCEVs should achieve lifecycle cost parity with conventional vehicles and the hydrogen fuel cost should be significantly lowered. Technology advances and demonstration on large scale have significantly lowered the cost of many hydrogen applications in the transport and energy sectors. Further technological developments and improvements along the value chain are still necessary to reduce cost and ensure cost-competitiveness with other fossil-based applications, thus ensuring global market uptake.

According to a recent study from the Hydrogen Council, a global organisation gathering stakeholders from the hydrogen sector, the main cost factor is the CAPEX of the equipment – namely the costs of components and manufacturing costs of the car itself – which represents almost 70 % of the TCO [Hydrogen Council 2020]. There is a significant potential of cost reduction by optimizing the manufacturing process and improving the technology further. This is one of the main challenges addressed by H2020 INN-BALANCE project that focuses on the development of reliable and cost-efficient Balance of Plant components for passenger car fuel cell systems. Several projects and initiatives across Europe invest time and resource to increase the competitiveness of hydrogen applications. Several German Fraunhofer Institutes work for instance on new manufacturing methods and technologies to lower the production cost of a 100 kW fuel cell system to approximately 5000€ – less than 10 % of the current costs [Fraunhofer 2021].

Experts from the Hydrogen Council estimate that the fuel cell stack for passenger vehicles will experience learning rates of 17 % in average over the 2020–2030 decade provided that an annual production volume of several hundred of thousand fuel cell-based vehicles is reached every year. It is assumed that the market uptake of FCEV will also contribute to a more efficient use of this infrastructure with higher utilization rate. This would allow operators of gas stations to build bigger hydrogen refuelling stations with higher hydrogen capacity, which is expected to reduce hydrogen fuel cost by at least 50 %, to between 4 or 5 $ per kg (instead of 10 to 12 $ / kg today) [Hydrogen Council 2020].

4.2 Future steps and note to our readers

A new EU platform for hydrogen – European clean hydrogen alliance

The European Commission officially launched in July 2020 the European Clean Hydrogen Alliance as part of its new industrial strategy which is to develop key strategic value chains in Europe to achieve the European Green Deal objectives. The goal of this alliance is to support the development of a clean and globally competitive hydrogen industry in Europe. The alliance will play a crucial role in implementing the actions of the European hydrogen strategy. This organization, which brings together industry, national and local public authorities, civil society and other stakeholders, should support the scaling up of production and demand of low-carbon hydrogen. 500 companies have already joined the alliance in 2020 and this number is expected to reach 1000 by 2024 [European Commission 2020b].

The momentum for green hydrogen and all related applications is growing fast. Almost every month a new initiative is announced, and new actors join the hydrogen sector. The authors of this short INN-BALANCE handbook hope that the hydrogen and energy transition will continue and even be accelerated after the Covid crisis. We encourage our readers to follow the activities and support the actions of the European Clean Energy Alliance or any other national and regional hydrogen initiatives. We are committed to ensuring that INN-BALANCE technologies are used in future fuel cell vehicles and systems.

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Fuel cells are a mature technology ready for scale-up in the automotive market. It is now about driving manufacturing forward by reducing production costs, while increasing the overall efficiency and reliability of fuel cell components and systems.

INN-BALANCE is an EU project funded by the Fuel Cells and Hydrogen 2 Joint Undertaking tackling this question. INN-BALANCE focuses on the improvement of Balance of Plant (BoP) components for automotive fuel cell systems through design optimisation, testing of innovative components and modules, and the assembly and testing of the complete fuel cell system under laboratory and automotive conditions. Nine partners from five countries are involved in the project.

Balance of Plant components include compressors, pumps, sensors, heat exchangers, humidifiers, recirculation blowers, etc. In INN-BALANCE, four different modules, each consisting of several BoP components were studied and optimised: the cathode module and the anode module supplying respectively air and hydrogen to the fuel cell stack, the thermal management system keeping all components at a desired temperature and the control system ensuring smooth operation.

This guidebook presents the main project activities and results generated during the project. It also contains an overview of the current market for hydrogen vehicles in Europe and provides an outlook to future challenges in this field. The main target groups of this document are vehicles OEMs and their suppliers, fuel cell integrators and manufacturers, BoP manufacturers, research institutions, and public authorities.

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