Publishable Summary of the 2nd Periodic Report

HEALTH-CODE

"Real operation pem fuel cells HEALTH-state monitoring and diagnosis based on dc-dcCOnverter embeddeD Eis"

Grant Agreement n° 671486
Research and Innovation Project

Contents

Explanation of the work carried out by the beneficiaries and Overview of the progress

1. Context, Objectives and Approaches

Context

Fuel cell technologies are currently spreading in the public market due to the great technological improvements achieved in the last decades. Nevertheless, their reliability, availability and durability are still below competitive values with respect to conventional power systems. The on-board implementation of suitable control, diagnostic and prognostic algorithms can improve such features, making fuel cell more efficient and competitive.

> The HEALTH-CODE project aimed at improving and validating in emulated real operations an advanced Monitoring and Diagnostic Tool (MDT) capable of evaluating the State-of-Health (SoH) of Polymer Electrolyte Membrane Fuel Cell (PEMFC) systems for micro-Combined Heat and Power (μ-CHP) and backup applications. The developed tool is based on the use of suitable data derived from Electrochemical Impedance Spectroscopy (EIS) measurements performed during system operation. In the available literature, EIS has been widely recognized as an effective technique to extract valuable information by means of just one measurement process. Before HEALTH-CODE such method was applied only for laboratories use due to its costs and complexity. HEALTH-CODE solutions leverage EIS advantages while ensuring the design of proper hardware for on-board uses, bridging laboratory and on-field applications.

The HEALTH-CODE project, stemming from EU project D-CODE[1] (FCH JU FP7, G.A. No. 256673), has focused on the enhancement of both EIS board technology and diagnostic algorithms, bringing the MDT from Technology Readiness Level (TRL) 3 of the D-CODE project up to TRL 5 and developed hardware (EIS board and DC/DC converter) up to TRL 6. The EIS board cost has been proved to cost less than the 3% of Total Cost of Ownership (TCO).

Objectives

HEALTH-CODE has set the following three main technical objectives:

- the enhancement of EIS-based diagnosis for residential μ-CHP and backup applications;
- the development of a Monitoring and Diagnostic Tool (MDT) for State-of-Health (SoH) assessment, fault detection and isolation as well as degradation level analysis for lifetime extrapolation;
- the reduction of experimental campaign time and costs by means of innovative scaling-up methodology.

The **first objective** of the HEALTH-CODE project consists in the improvement of the tool hardware parts. The EIS board and the DC/DC converters were reengineered to enhance interfacing with system control

---

[1] D-CODE achieved the development as proof of concept of an innovative electronic board that allows performing EIS measurements by acting on DC/DC converters, properly interfaced with the accounted backup PEMFC system. Suitable diagnostic algorithms were developed to perform monitoring and diagnosis with respect to two cell failure modes, related to water management (i.e., membrane drying and cell flooding) and reactants (i.e., air starvation) issues - https://cordis.europa.eu/project/rcn/97932/reporting/en.

and power electronics. Optimized functionalities were introduced to allow off- and on-grid uses, improve signal-to-noise ratio as well as to reduce production costs while ensuring proper monitoring and diagnostic performance.

The **second objective** of the project is the enhancement of the algorithms used for stack monitoring and diagnosis to detect and isolate five failure modes[2]. Diagnostic algorithms inference is used to assess the State-of-Health (SoH) of the system under analysis and to support Residual Useful Lifetime (RUL) estimation as well. In addition to model- and data-based approaches, already investigated during D-CODE project, active diagnosis method has been also accounted focusing on cell breaks and crossover leakage.

The **third objective** is a proper scaling-up approach able to extend single cell/short stack behaviours to full stack. In such a way it is possible to reduce equipment costs, since single cells requires smaller and cheaper testing devices, and account for operating conditions which cannot be tested on full scale.

Approach

> The three main objectives are achieved by the project, whose framework is structured into three main pillars, that are i) hardware and power electronics, ii) monitoring and diagnostic algorithms and iii) experimental analysis.

Concerning the **first pillar**, the PEMFC systems tested under the framework of the HEALTH-CODE project are an air-fed µ-CHP system, manufactured by BPSE, and a backup O_2-fed system, manufactured by EPS. A significant innovation with respect to the current scenario consists in the investigation of a system fed by pure oxygen in addition to a conventional one fed with air. EPS oxygen-fed system is well suited for backup applications either in large or local grids, since such configuration allows energy storage converting excess electric energy into hydrogen and oxygen form through the use of an electrolyser. High conversion efficiency is ensured through the direct use of oxygen, also avoiding possible contamination due to polluted surroundings. Moreover, higher energy density and efficiency are also achieved if compared to those of conventional backup systems. Therefore, from both industrial and scientific perspectives, EIS-based diagnostics for O_2-fed systems is a novel achievement not yet addressed by previous projects.

Another central issue of the first pillar is design and manufacturing of the EIS board, which controls the DC/DC converter to perturb the stack current and acquire, at the same time, the voltage to derive the impedance spectrum. Two DC/DC converters were considered, one for each analysed system. The converter for the BPSE system was designed from the scratch, to optimize its features for the correct interfacing with the EIS board and to guarantee reliable EIS measurement. The converter for the EPS system was modified to be interfaced with the EIS board, thus demonstrating the possibility to easy implement the EIS on board of existing system with minimal technical effort.

The **second pillar** relates to monitoring and diagnostic algorithms. In HEALTH-CODE three different types of algorithms were considered: a model-based algorithm was developed by UNISA through an Equivalent Circuit Modelling (ECM) approach, a data-based algorithm was designed by UFC following a fuzzy clustering approach, a data-based algorithm was developed by EIFER through ANFIS approach and a data-based algorithm was proposed by AAU based on active diagnosis approach. The main innovation concerning these algorithms is their characterization on the two considered systems and on five failure modes, that are i) major change in fuel composition (reformer/electrolyser malfunction or bad fuel

---

[2] Herein failure mode designates an operating status occurring when one or more faults lead to the inability of the system to perform its minimum required function.

quality), ii) air starvation, iii) fuel starvation, iv) sulphur poisoning and v) water management issues (i.e., flooding and drying). This significant advancement aimed at extending algorithms performance over a larger range of faulty states and fuel cell technologies with respect to what available in the literature. Moreover, the connection between current SoH of the fuel cell system and its RUL are also deepened, to introduce a preliminary lifetime estimation which can be a valuable information for mitigation strategies design and future application.

The **third pillar** deals with the experimental analysis, which had a twofold role: on the one hand, it provided significant data for monitoring and diagnostic tool design and validation; on the other hand, this analysis aimed at highlighting the impact of the faults on the stacks of the two investigated FC systems. The effects were studied by inducing the faults with increasing magnitudes according to accurate testing protocols, properly designed upon knowledge derived from previous projects[3]. Moreover, the study was performed on both short and full stacks as well as on the systems, supporting the design of proper scaling-up methodology.

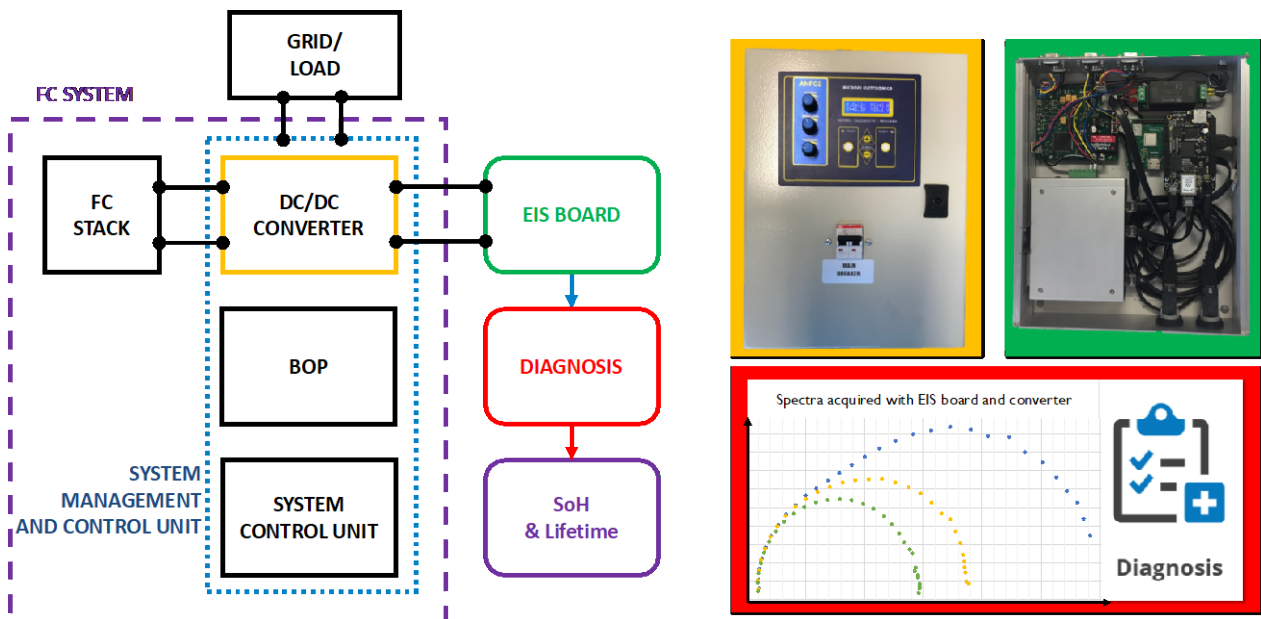To summarize, Figure 1 gives a schematic representation of the main elements of HEALTH-CODE.

Figure 1 – Schematic representation of grid connected fuel cell system (purple box), through DC/DC converter (yellow box) and EIS board (blue box) and system control unit (black box). The connection with the monitoring and diagnostic tool components (red box) is also proposed, with all considered steps such as state of health characterization and lifetime extrapolation.

The scheme of Figure 1 draws the logic behind the project concept and the links among the main features and components. In HEALTH-CODE a great attention was given to hardware device and power electronics (i.e., grid/load interface, DC/DC converter and EIS board) to guarantee the future development and implementability at industrial scale. On the other hand, the deep technical knowledge on fuel cells operations and fault diagnosis represents the starting point of the innovative outcomes of HEALTH-CODE project.

2. Description of the work and main results achieved

Below the list of the main results achieved at M40 (December 2018) by HEALTH-CODE project is reported in the list below:

---

[3]As for instance the STACK TEST project (FCH JU FP7, G.A. No. 303445) results.

- EIS board design, manufacturing and validation;
- High voltage (HV) DC/DC converter design and commissioning;
- Low voltage (LV) DC/DC converter modifications and testing;
- Experimental test protocol and fuel cells characterization on FC systems;
- Stack EIS measurements performance, in nominal and faulty conditions, for both FC technologies;
- Monitoring and diagnostic algorithms design and validation;
- Scaling-up algorithm design and validation;
- HW/SW integration of diagnostic tool into FC systems;
- Systems EIS measurements performance, in nominal and faulty conditions, for both FC technologies.

No relevant issues were encountered, and those experienced were suitably solved; this has allowed the recovering of some delays occurred, driving all activities towards their planned completion. In the following is given an overview of the achievements, grouped with respect to the project's pillars.

Hardware and power electronics

This part of the project was finalised to the coupling of the EIS board with the two converters and the validation of EIS measurements during on-board operation.

For the design and manufacturing of the EIS board and converters, required for the two investigated systems, great attention was given to current and voltage signals acquisition. The same activity was performed at the fuel cell terminals of the DC/DC converter, to ensure the right current perturbation. The starting point for EIS board release was the concept from the D-CODE project, from which a first board version was prototyped (proto 1). Afterward, a second version (proto 2) was designed to have better performance in terms of data acquisition and processing. The final assembly is reported in Figure 2, which shows the footprint of the box with respect to conventional lab equipment. This makes the board suitable for stand-alone applications and potentially for lab applications. This latter option was explored during SSERR workshop for further exploitation of the project outcome (see the Lean Canvas of Figure 21).

Figure 2 – Final assembly of EIS board proto 2 compared to conventional lab equipment.

The board has also been tested to assess noise performance. Both inter-processors protocol and communication have been defined and implemented; moreover, real time software coding and testing has been also fulfilled. Figure 3 shows the set of available connection ports for the purpose of testing and validation activities.

Figure 3 – Final assembly of the EIS board proto 2 (up-left) with embedded external connections (up-right; down-left). Insight of the interior parts (down-right).

With respect to the DC/DC converters, the ad hoc BPSE HW was designed by UNISA for the maximum efficiency (up to 94%) and features grid connection; it was and manufactured by Micropi Company. Concerning the LV DC/DC converter for the EPS backup system, the required modifications for the correct interfacing with the EIS board were successfully implemented upon the basis of the technical guidelines provided by BITRON and UNISA. During the development phase some tests were performed to verify the communication protocols between board and converters. Pictures of the test bench and the performed tests on the investigated FC systems coupled with the EIS board and converters is presented in Figure 4.

Figure 4 – On the left side, the test bench setup for BPSE system: EIS board proto 2 (with HMI interface) plus external DC/DC converter; on the right side, , the test bench setup for EPS system: EIS board proto 2 is directly linked to internal DC/DC converter. Both systems are controlled via LabView panel (external monitors).

By the end of the project, the total amount of hardware prototypes is summered in the table below:

Table 1 – Number of prototypes manufactured during the project.

	EIS board (proto 1)	EIS board (proto 2)	DC/DC converter
Quantity	2	4	1

Experimental analysis

The experimental activity in HEALTH-CODE project was performed on the stacks in both stand-alone (i.e. un test bench) and operative configuration as a commercial product; in this latter case the stacks are mounted on their original systems, connected to BoP and controlled by the original management tool. The experimental campaign was mainly performed during period 1, while the testing on the system was accomplished during the last part of period 2. Proper test protocols were defined to increase, on the one hand, the information which can be retrieved with the experimental activity and reduce, on the other hand, the amount of required experiments (and thus the time and cost for the related campaign).

In total, more than 2300 EIS spectra were acquired at the lab premises; from the initial analysis it was estimated that about 1200 EIS spectra would have been needed for the purpose of the project. The extra spectra were measured to deepen the analysis performed on O_2-fed stack and on aged stacks, other spectra were acquired on single cells in stack to better validate the scaling-up algorithm. Of those spectra the 10% were measured at stack level and the remaining at cell level. The 25% of the total amount refers to EIS acquired in nominal conditions, while the 75% in faulty conditions. The following picture shows the shares of the investigated conditions.
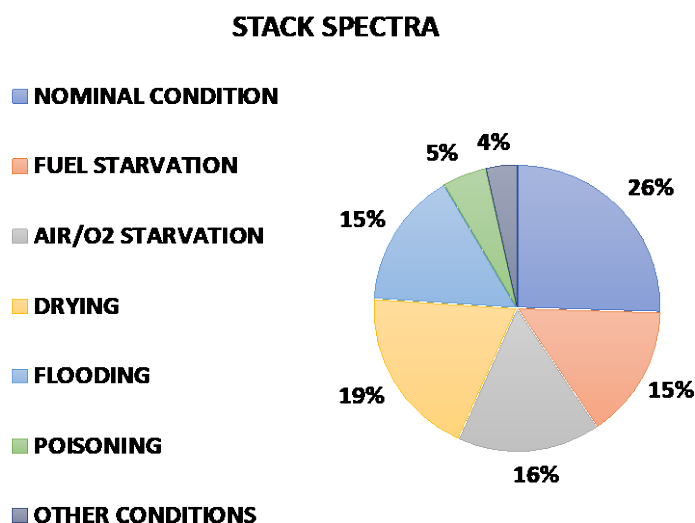

Figure 5 – Test scheduling among the partners involved in the experimental characterization, with percentage of acquired EIS spectra in respect of the operating condition. "Poisoning" refers to CO contamination and sulphur poisoning; "other conditions" gathers all non-faulty condition such as increase of temperature or small variation of reactants stoichiometry level.

The characterization of the stacks in nominal conditions was achieved successfully and all six faults – of 5 failure modes – tests were completed in time. The large amount of EIS spectra information have been collected in a **spreadsheet database**, shared among the partners. This database, to the knowledge of the consortium is one of the largest available for FC PEM technologies and contains original information on the behaviour of O2-fed PEM stacks. The building and the managemenT of the database was not planned in the DoA, however it was decided to build a catalogue all valuable information on the acquisitions and to tag the EIS spectra for an easy-to-use access for future exploitation (i.e. monitoring and diagnostic algorithm improvement as well as for lifetime characterization).

Both technologies underwent tests concerning electrodes flooding, membrane drying, reactants starvation and poisoning conditions (CO contamination and sulphur poisoning for air-fed technology). An example of the EIS spectra acquired at each testing facility in both nominal and faulty conditions for each technology is shown in Figure 6. In particular, the pictures show EIS spectra at 40 A for BPSE and 210 A for EPS; these current levels are chosen as reference for the diagnostic tool validation (discussed hereafter).

Figure 6 – Examples of EIS spectra[4]: spectra acquired at EIFER and AAU laboratory (blue box); spectra measured at UFC facilities (red box).

Through these pictures it can be analysed the difference between the behaviour shown by an oxygen-fed stack with respect to that of an air-fed one under both normal and faulty operations. It is worth observing that, the spectra acquired by EIFER and AAU show two visible arcs that warp under faulty states. On the other hand, the spectra measured on EPS short stack by UFC show instead one visible arc, which, as well, changes its shape under faulty conditions. Moreover, one can observe a specific change of geometrical

---

[4] Values are not shown for the sake of confidentiality.

shape of EIS spectrum according to the related operating condition, thus leading to a suitable diagnostic tool implementation. Moreover, the poisoning conditions represent a key-feature of the developed database (only few data are currently available from the state-of-art). The results achieved by experimental campaign were useful to develop analytical and empirical relationships among EIS spectra and faults, this is one highly valuable outcome of HEALTH-CODE.

At system level, final testing set-up was configured as shown in Figure 4. Each test in faulty condition was obtained with respect to a specific sequence of manoeuvres, which take into account fault type, fault magnitude, system technology and safety limitations[5]. The experimental campaign has been performed under limited operating conditions according the test matrix here reported.

Table 2 – Test matrix for system testing. Refer to D5.1 and D5.2 for technical explanation.

	Nominal	Fuel Starvation	Air/O$_2$ starvation	Flooding	Drying	CO contamination	Sulphur poisoning
BPSE system	X	-	X	X	-	X	-
EPS system	X	X	X	X	X	Not scheduled*	Not scheduled*
* These two faults can't occur in a system fed with pure hydrogen.							

System test configurations are shown in Figure 7. The backup system manufactured by EPS has been tested at UFC premises, whereas µ-CHP system at BPSE premises.
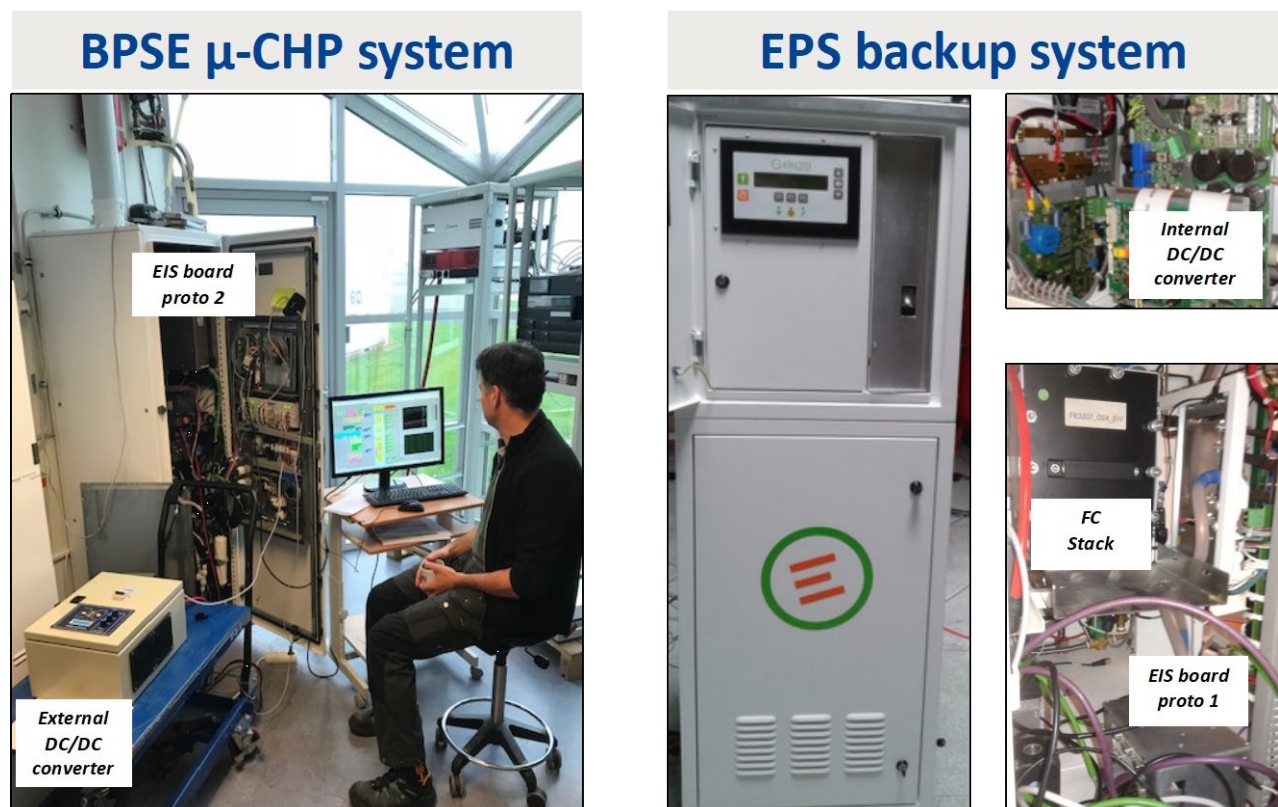

Figure 7 – System Test benches equipment for laboratory testing: (left) BPSE µ-CHP system, (right) EPS backup/energy system. Both systems have been tested with EIS board proto 1 and, afterwards, with proto 2 as well.

---

[5]Further details are available in the related Deliverable 5.1 "System Testing Procedure".

The EIS data and the results collected in all the defined conditions were recorded by the EIS Board installed on the systems running in environments reproducing real operations. The spectra recorded on the systems are presented in Figure 8 and Figure 9 showing good quality of the EIS curves.
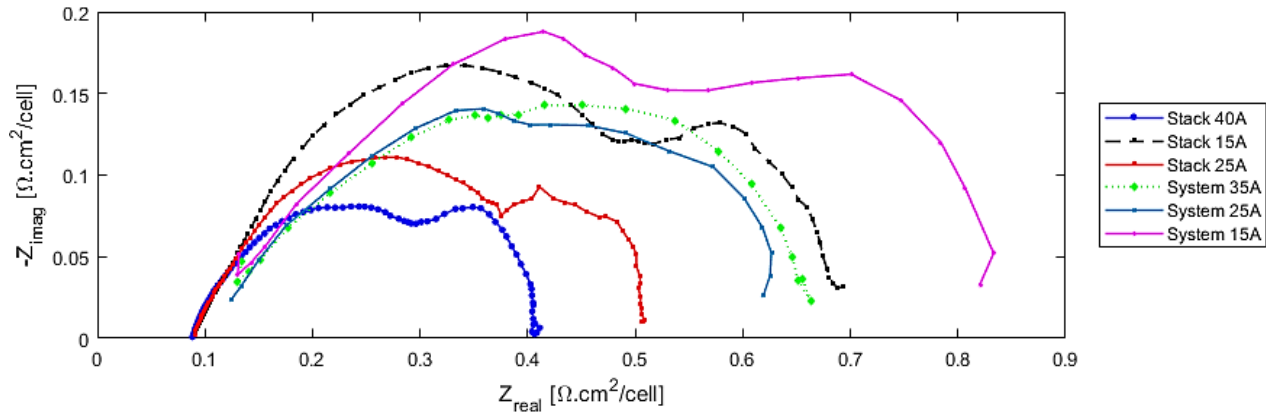

Figure 8 – Comparison between EIS spectra acquired on stack and system for air-fed technology in nominal condition.

For BPSE tests (Figure 8), the same size and type of fuel cell stack (46 cells, water-cooled fuel cell stack) was used both for stack testing and for the grid-connected system testing. However, due to dilution and the presence of impurities in the reformate gas of the fuel cell system and other system specific losses, the impedance spectra are consistently larger at system level. The fuel composition in the laboratory simulated reformate gas, but in the real system the fuel cell has been directly coupled with a natural gas reformer. However, the shape and the features of the EIS curves have been seen to scale consistently, and the diagnostic tool doesn't need any further characterization once installed, only a tuning might be needed.
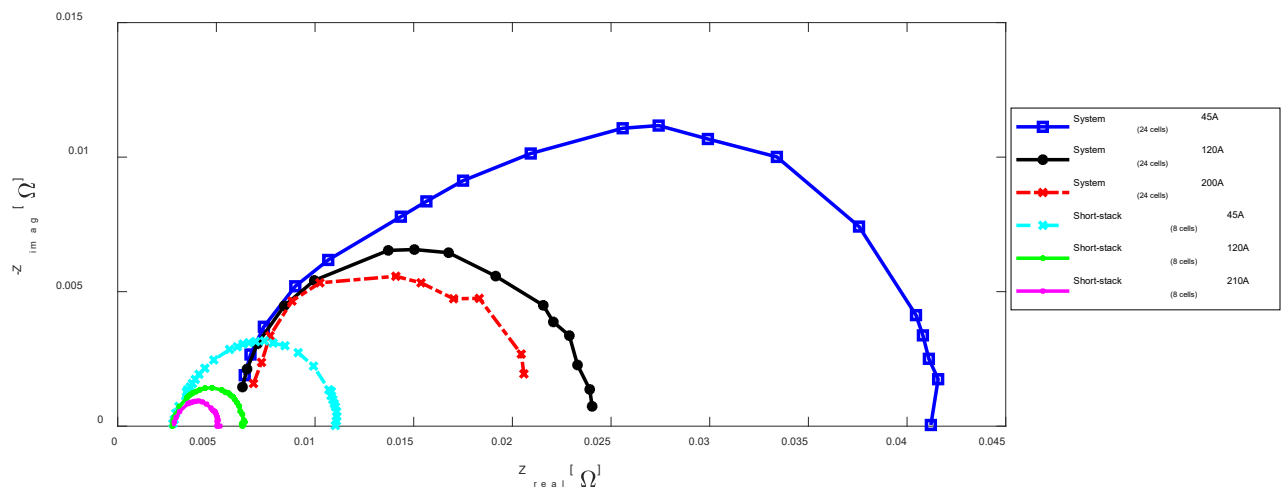

Figure 9 – Comparison between EIS spectra acquired on stack and system for O_2-fed technology in nominal condition.

For EPS tests (Figure 9), the system spectra are bigger than those derived for the short-stack ones. This is particularly due to the fact that the system's stack has 3 times the number of cells in respect of the short-stack. Moreover, other mechanisms impact the system measurements, such as a different impedance due to the connections and an operating temperature less than the one imposed during the laboratory tests. However also in this case the shapes are consistent with the short-stack. This result confirms the original idea to implement a scaling-up methodology to derive the full stack EIS curves from short-stack/single-cell.

As regards practical issues for on-board implementation and application, it is worth noting that the time required for a spectrum measurement can vary from 2 to 15 minutes depending on the number of the selected frequencies and number of samples.

Finally, concerning the scaling-up algorithm, this method exploits the physical knowledge of the involved phenomena to derive non-dimensional parameters able to describe the considered physics in several cases. EIS spectra from single cell or short stack are used as reference to extract non-dimensional parameters by means of the ECM approach, whose general description is available in the next section and sketched in Figure 14. The parameters are then arranged in a non-dimensional fashion making use of the Buckingham Pi theorem. Through these parameters, the impedance can be reconstructed at different stack sizes (i.e., scaling-up in size) or operating conditions (i.e., scaling-up in current, temperature, humidification, etc.). A schematic representation of the steps required by the proposed algorithm is presented in Figure 10.
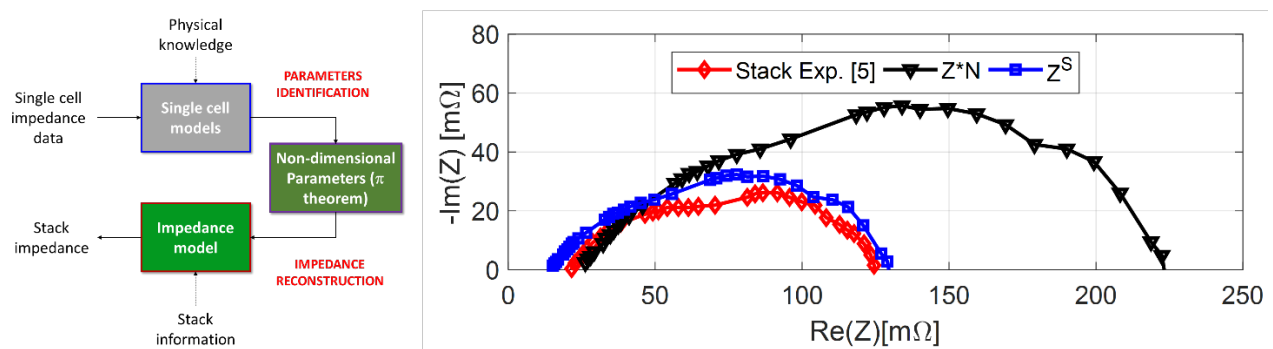

Figure 10 – Schematic representation of the scaling-up approach [6] and final results on EIS acquired on EPS stack.

Scaling-up algorithm can reduce fuel cell testing costs by extrapolating full stack performance and impedance behaviour from single cell and/or short stack. The major advantage of the proposed algorithm consists in its feasibility for online uses, thanks to low computational burden, while maintaining good accuracy. Moreover, it can be applied for different scopes, such as design, control, diagnostics, SoH monitoring and prognostics. The validity of the approach has been proved by using experimental data available from the project campaign within the WP2 as described by Figure 10. As one can observe, the experimental EIS spectrum at stack level (red line) of O_2-fed technology is well represented by the scaled EIS spectrum of the cell (blue line).

Monitoring and diagnostic algorithm

The aim of such pillar was the development of a Monitoring and Diagnostic Tool (MDT) capable of evaluating the State-of-Health of the FC systems and inferring on its lifetime. Several approaches have been considered and listed below and classified per involved partner:

- AAU: active diagnosis based on FC response evaluation to random stimuli;
- EIFER: signal-based diagnosis through Adaptive Neural Fuzzy Interference System (ANFIS) approach;
- UFC: data-based diagnosis through Fuzzy Clustering approach;

---

[6] Russo L., Sorrentino M., Polverino P., Pianese C., Application of Buckingham π theorem for scaling-up oriented fast modelling of Proton Exchange Membrane Fuel Cell impedance, Journal of Power Sources 353 (2017) 277-286. Polverino P., Bove G., Sorrentino M., Pianese C., Generalized scaling-up approach based on Buckingham theorem for Polymer Electrolyte Membrane Fuel Cells impedance simulation, Energy Procedia, Vol. 158, Feb. 2019, Pp 1514-1520.

- UNISA: model-based diagnosis through Equivalent Circuit Modelling (ECM) approach, combined with waveform analysis for preliminary faults identification.

The EIFER, UFC and UNISA algorithms are developed for on-board application. The very first step towards algorithms completion consists in the extraction of significant features from the measured EIS spectra to be used as proper indicator of the SoH of the system. Then, the off-line evaluation of the algorithms has been achieved by training and validation phases. Consequently, the algorithms have been optimized in order to be implemented on the EIS board and, finally, validated on the systems running under real load conditions.

A common data-set of acquired EIS spectra has been properly chosen to balance algorithms training and validation phases. The off-line procedure has been performed at 40 A for BPSE system and 210 A for EPS system (i.e. the operating current level of both investigated systems).

	TRAINING	TEST
TOTAL	**56**	**20**

	TRAINING	TEST
TOTAL	**55**	**33**

Figure 11 – Data-set of EIS stack spectra. Acronyms: NC – nominal condition; FS – fuel starvation; AS – air/O$_2$ starvation; DR – drying; FL – flooding; CO – CO contamination; SP – Sulphur poisoning.

Subsequently, some performance indicators[7] (see Table 3) have been extrapolated for diagnosis methodology evaluation. The *precision* indicator is defined with respect to the correct detection of the diagnosed healthy conditions. While the *accuracy* indicator is assessed by the correct identification, either faults or normal operations. The complement of the *accuracy* is assumed as *error* indicator. The *recall for fault* gives the probability that the diagnosed condition matches with the real healthy one, while the general performance is quantified with the *F1* index that suitably combines the previous indicators. Algorithms final methodology and performance results are hereafter presented.

The design process of the ANFIS-based diagnostic algorithm performed by EIFER has entailed the development of a Fuzzy Interference System (FIS) structure by means of an Adaptive Neural Network (ANN). Together they form an Adaptive Neuro-Fuzzy Inference System (ANFIS) as shown in Figure 12 with FIS maps, an input space to an output space made using fuzzy logic approach. Three main steps are implemented: i) fuzzification step, which converts a non-fuzzy input to a fuzzy input, ii) defuzzification step, which converts a fuzzy output to a non-fuzzy output, and iii) logic decision, which uses If-Then rules to decide on the appropriate output membership function.

---

[7] Cadet C., Jemei S., Druart F., Hissel D., Diagnostic tools for PEMFCs: from conception to implementation, International Journal of Hydrogen Energy 39 (2014) 10613 – 10626.
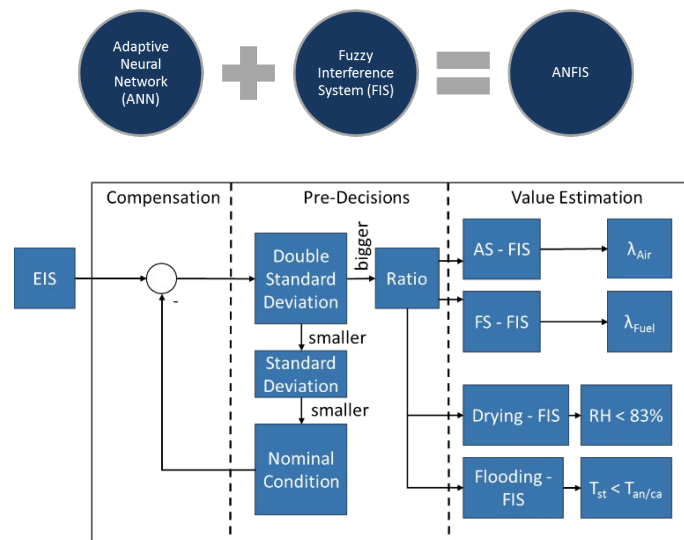
Figure 12 – Logic scheme of a Fuzzy Interface System (FIS) for fuel and air starvation and water management faults.

The algorithm developed by UFC is based on fuzzy clustering approach as well (see Figure 13). It is composed of three steps. The first step is the determination of a features space in which the different faults can be discriminated. The second step is the learning one, where EIS are measured in known operating conditions, the features determined in the first step are then extracted then the clusters are built for stack SoH, which are automatically identified. These first two steps are made off-line. The third step is performed on-line: when a new measurement is carried out, it is automatically classified in one of the clusters, determining the SoH of the stack. SoH clusters have been identified upon features distribution, achieving algorithm validation.

Figure 13 – Fuzzy Clustering approach methodology proposed by UFC.

The model-based algorithm conceived by UNISA exploits, instead, an Equivalent Circuit Model (ECM), whose parameters (tightly linked to physical phenomena) have been assumed as representative features for fault detection and isolation. An example of ECM features extraction and diagnostic methodology is proposed in Figure 14. Upon identification of parameter values, their distribution in normal and faulty states has allowed the creation of a Fault Signature Matrix (FSM) during the off-line training phase. The normal behaviour represents the reference state through which fault detection is performed: any deviation triggers an alarm with respect to the related ECM parameter. Then, the specific behaviour shown by the parameters under the different faults outlines the reference pattern through which fault isolation is performed (off-line validation phase). It is worth noting that the algorithm for parameters identifications exploits a patent filed by UNISA during the FCH JU project D-CODE[8]

Figure 14 –UNISA ECM-based approach: the first four plots show the fitting process by means of the ECM; the bottom right pictures illustrate the isolation process by identifying the fault pattern into the FSM.

These three approaches have good genericity, since they can be easily transferred from one technology to another. Moreover, their online features are reasonably good: are very fast (low computational burden and short processing time) and need limited expertise from the user. The final results of off-line validation are summarized in Table 3 (refer to D4.4 for more details).

---

[8] Petrone R., Polverino P., C. Pianese, M. Sorrentino; Method and apparatus for monitoring and diagnosing electrochemical devices based on automatic electrochemical impedance identification; Patent n. WO/2016/071801.

Table 3 – Performance indexes results of EIFER, UFC and UNISA algorithm for off-line validation. The figures show global evaluation for both BPSE and EPS EIS data.

GLOBAL	Off-line Performance index				
	Precision	Recall for fault	F1	Accuracy	Error
EIFER	1.00	1.00	1.00	1.00	0.00
UFC	1.00	1.00	1.00	1.00	0.00
UNISA	1.00	0.83	0.91	0.97	0.03

Then, the proposed diagnostic tool (embedding the three aforementioned algorithm) has been validated in real load operation. The time required for the state-of-health assessment and the faults' classification on both the systems, plus the time for measurements and communications, is suitable for diagnostic purposes. The tool was able to acquire the EIS spectrum and process the data in a short time (few minutes). The following table shows the qualitative results related to detection and isolation efficacy of the complete tool, obtained during the experimental activity on the real systems:

Table 4 – Qualitative results for MDT fault detection and isolation for both system validation. Some faulty conditions are not scheduled or not available for system testing.

system	On-line Qualitative index					
	FS	AS	FL	DR	CO	SP
EPS	🙂🙂	🙂🙂	🙂🙂	🙂	not scheduled	not scheduled
BPSE	■	🙂	🙂	■	🙂	■

Moreover, the MDT tool has been embedded by UNISA (not set as DoA expected result) with Human-Machine Interface (HMI) for the purpose of user-friendly testing procedures and future exploitable applications. Through a touch-monitor, the operator can easily set the EIS acquisition, trigger the diagnostic tool and, finally, analyse the results. Figure 15 shows an example of a real output alarm obtained on BPSE system during a test session under induced fault. The interface shows the spectrum acquired under real load operations (red points) and the corresponding model (blue points) by using the UNISA algorithm. It is easy-to-understand the quality of the acquisition and the resulting data elaboration. Moreover, the diagnostic algorithm displays the recognised operating conditions (e.g. air starvation). When the nominal condition is detected and isolated, no alarms are displayed; under faulty conditions an alarm is triggered. This interface may be exploited to allow on-field maintenance and likely remote diagnosis.

Figure 15 – HMI example of MDT (UNISA approach). The screenshot is taken from the interface show on the bottom-left side of Figure 4.

Finally, the active diagnosis algorithm developed by AAU was oriented towards specific fault types in accordance with manufacturer interests, conceived as a complementary approach to the current on-board controls. The accounted failure modes are related to cell breaks/crossover and CO poisoning. Specific routines have been identified and dedicated tests assess their validity (see Figure 16).
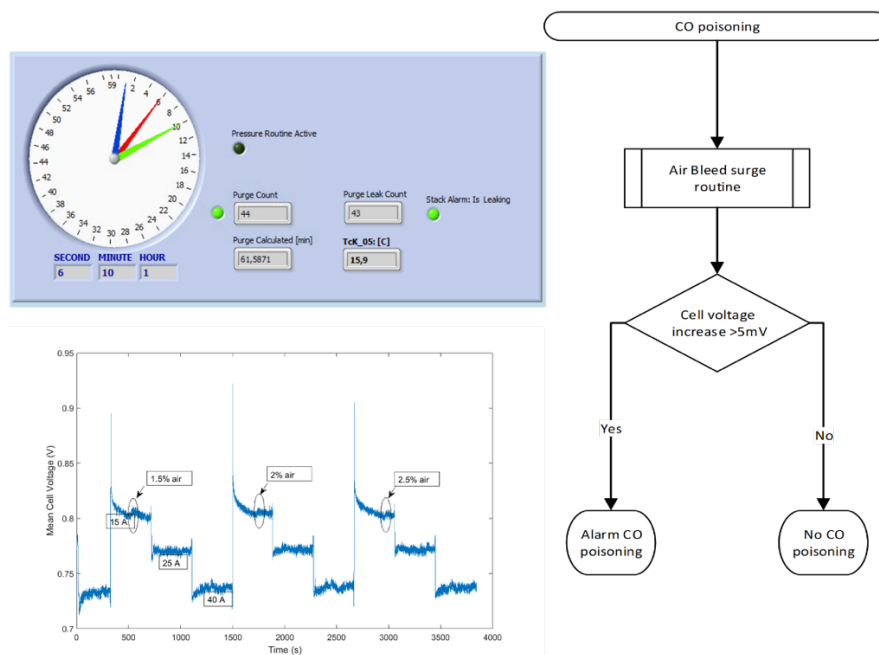

Figure 16 – Active diagnosis approach for CO detection by air-bleed routine. Main cell Voltage is presented along with the graphic interface implemented on BPSE system.

As far as the lifetime concerns, the metrics derived from the EIS spectra were used to follow the evolution of the stack total resistance, which is assumed as an indicator for the overall degradation. It has been shown in the D4.4 how the resistance of the EPS stack increased in time after a sequence of operating

conditions outside their nominal range of variability (e.g. low-high lambda, flooding, oxygen starvation, drying, fuel starvation).

Finally, it can be stated that the MDT tool along with its on-board implementation was successfully validated in terms of efficacy, reliability, cost and easy HW/SW integration; thus, making it worth for further development and applications such as advanced control and maintenance management optimization.

3. Exploitation and dissemination of results

The innovations of the HEALTH-CODE project have been promoted through three main communication channels, that are: the project website, scientific workshops and publications (i.e., conference and journal papers, brief technical reports, etc.). The website pemfc.health-code.eu is available for public access, giving an overview (constantly updated over the project period) of objectives, significant results, dissemination actions, financial and technical status and main news and events. Moreover, a private access was given to project partners to share documents and data.
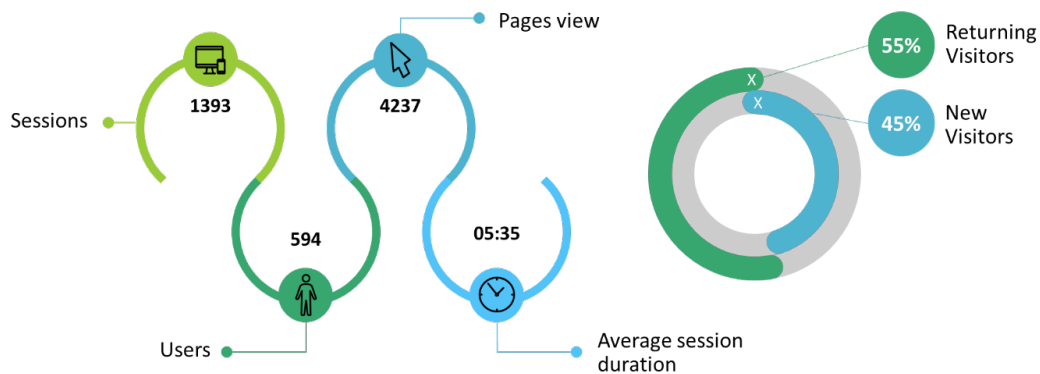

Figure 17 – HEALTH-CODE Website statistics at M40 (December 2018)

The main objectives of the dissemination and exploitation actions concerned:

- use the website as an interface between the project and the outside community;
- guarantee the external knowledge and awareness about the project;
- link the project with ongoing research initiatives;
- manage the foreground knowledge and its protection;
- set the actions for exploitation of results.

During Period 2, the project was presented at the FCH2-JU Programme Review Days held in Brussels on the 14th and 15th November 2018. A presentation was given by HEALTH-CODE coordinator during the Session V - Next Generation of Products – Energy. A poster (see Figure 18) along with the EIS board demonstrator was shown during the 2-days session. Second version of flyers was distributed (see Figure 19).
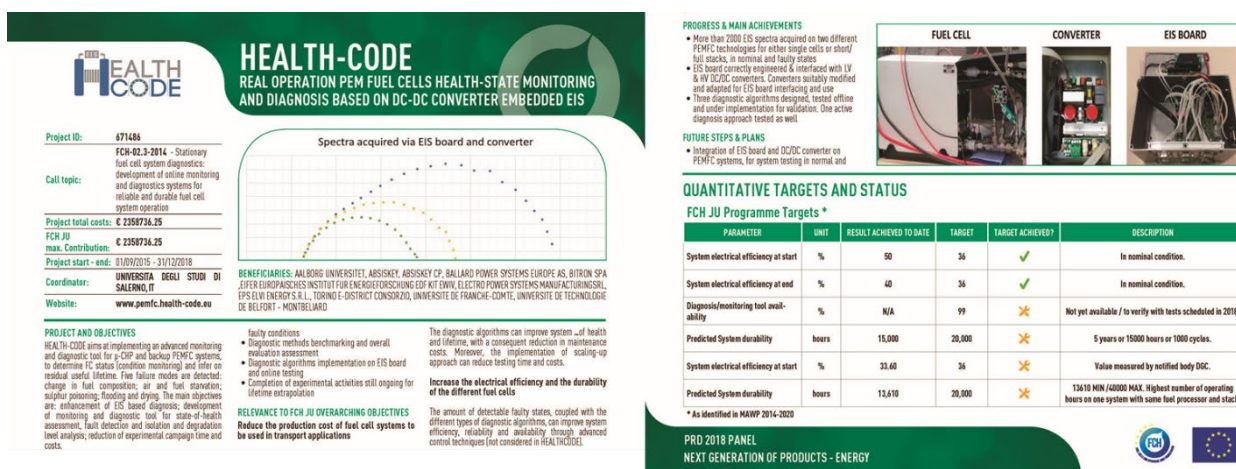
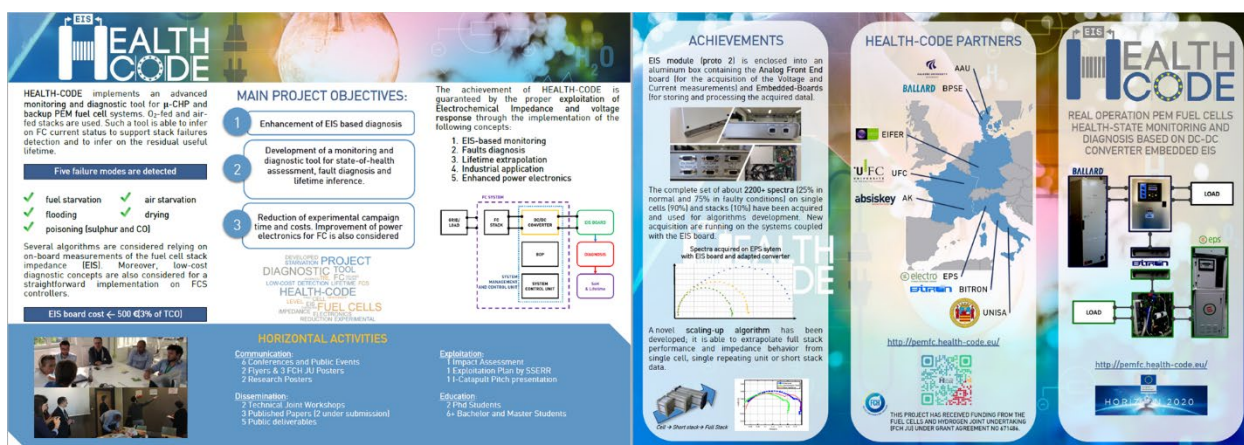Figure 18 – HEALTH-CODE poster presented during the Programme Review Days 2018.

Figure 19 – HEALTH-CODE final flyer.

Two joint workshops were organized in collaboration with the project DIAMOND[9] and INSIGHT[10], respectively. The first workshop was held on 4th July 2017 during the 6th European PEC & Electrolyser Forum in Lucerne (CH) – Congress Center KKL (45+ attendants). The second workshop was held on 13th November 2018 before the Programme Review Day 2018 in Brussels (B) - Manos Conference Center (60+ attendants). The workshops presented the most recent advancements concerning research on monitoring, diagnostics and control of both PEMFC and SOFC. The workshops gathered engineers and researchers from industry, academia and research institutions. A comprehensive overview and the exploitation potential of the project results were offered to the interested stakeholders and users at various levels. Invited guests from industry gave a further look into key topics tightly connected to monitoring and diagnostics of both PEMFC and SOFC. A final open discussion among the attendees was set to share experience and draft future paths towards FC improvements via on-board diagnostics. The pictures taken at both workshops are reported in Figure 20. All presentations given at both Workshops are available in the project website in the section Dissemination (https://bit.ly/2GfU6XT).

---

[9] DIAMOND: Diagnosis-aided control for SOFC power systems, FP7 FCHJU 2015/2018, G.A. No. 621208.
[10] INSIGHT: Implementation in real SOFC Systems of monitoring and diagnostic tools using signal analysis to increase their lifetime, FCH- 2 JU 2017/2019, G.A. No. 735918.

Figure 20 – (left) One Day Workshop on Monitoring, Diagnostics and Control for Fuel Cells - Improving fuel cells performance through innovative diagnosis and control (jointly organized with DIAMOND); (right) Workshop on Monitoring and Diagnostics of Fuel Cells -Innovative on-board diagnosis towards fuel cells performance enhancement (jointly organized with INSIGHT).

In the context of the common Exploitation Booster initiative, the consortium requested the assistance of the Services for Exploitation of Research Results (SSERR) and selected the service related to Business Plan Development (BPD). A consultant provided the service during the consortium meeting (20th-21st September 2018). Two Key Exploitable Results (KERs) arose from the HEALTH-CODE project (see Figure 21): early system status detection of Fuel Cells (Operations & Maintenance – O&M); data analysis for the Fuel Cells sector (Research Labs).
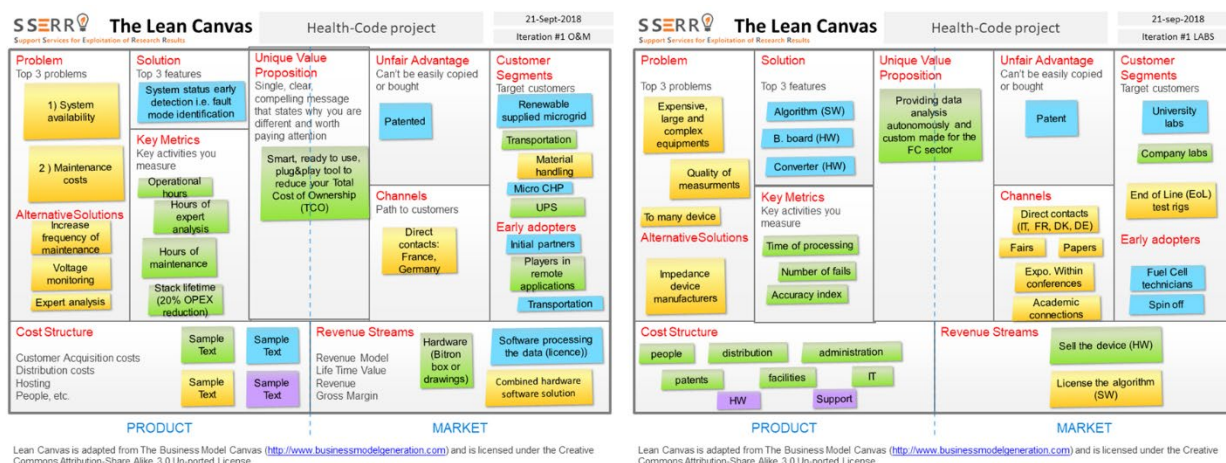

Figure 21 – Lean Canvas of O&M (left) and Research Labs (right) KERs[11]

Moreover, EIFER proposed HEALTH-CODE PROJECT for the I-Catapult[12] challenge. The objective was to capture innovations at an early stage and develop new ideas in a bottom-up process. In addition to identifying innovative and sometimes disruptive solutions, the event also served to collect ideas for upcoming events such as the Hacking Industry Camp organized by Electricité de Strasbourg and EDF in Alsace or the EDF Pulse Grand Est.

After the project closure, the HEALTH-CODE idea has been selected for the Piccard List Award 2019[13] held by the Constituent Assembly for the World Alliance for Efficient Solutions. HEALTH-CODE, jointly with
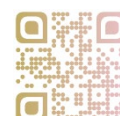
---

[11] Dissemination & Exploitation results are available on HEALTH-CODE website: https://bit.ly/2X38S9T

[12] Video of the event has been made and is available on HEALTH-CODE website: https://bit.ly/2X1OFBu

[13] More info available on the website: https://solarimpulse.com/efficient-solutions

INSIGHT project, exploited the positive outcomes of both projects in order to define a unique proposal that can guarantee both clean and profitable technologies for the environment.

Concerning academic research dissemination, seven papers were published, of which four during the second period:

- Russo, L., Sorrentino, M., Polverino, P., & Pianese, C. (2017). **Application of Buckingham π theorem for scaling-up oriented fast modelling of Proton Exchange Membrane Fuel Cell impedance**. *Journal of Power Sources*, *353*, 277-286. DOI: https://doi.org/10.1016/j.jpowsour.2017.03.116 (Open access)

- Petrone, R., Vitagliano, C., Péra, M. C., Chamagne, D., & Sorrentino, M. (2018). **Characterization of an H2/O2 PEMFC Short-Stack Performance Aimed to Health-State Monitoring and Diagnosis**. Fuel Cells, 18(3), 279-286. DOI: https://doi.org/10.1002/fuce.201700112

- Petrone, R., Yeetsorn, R., Harel, F., Hissel, D., Pera, M. C., Breaz, E., & Giurgea, S. (2017, December). **Accelerated Stress Tests Oriented Load Profile for PEM Fuel Cells Durability in Automotive Applications**. In *2017 IEEE Vehicle Power and Propulsion Conference (VPPC)* (pp. 1-5). IEEE. DOI: https://doi.org/10.1109/VPPC.2017.8330966

- Petrone, R., Pahon, E., Harel, F., Jemei, S., Chamagne, D., Hissel, D., & Pera, M. C. (2017, December). **Data-driven multi-fault approach for H2/O2 PEM Fuel Cell diagnosis**. In *2017 IEEE Vehicle Power and Propulsion Conference (VPPC)* (pp. 1-5). IEEE. DOI: https://doi.org/10.1109/VPPC.2017.8330974

- Buonocunto, G., Spagnuolo, G., & Zamboni, W. (2017, June). **A Kalman filter based approach to PEM fuel cell fault detection**. In *2017 IEEE 26th International Symposium on Industrial Electronics (ISIE)* (pp. 934-939). IEEE. DOI: https://doi.org/10.1109/ISIE.2017.8001371

- Simon Araya, S., Zhou, F., Lennart Sahlin, S., Thomas, S., Jeppesen, C., & Knudsen Kær, S. (2019). **Fault Characterization of a Proton Exchange Membrane Fuel Cell Stack**. *Energies*, *12*(1), 152. DOI: https://doi.org/10.3390/en12010152 (Open access)

- Polverino, P., Bove, G., Sorrentino, M., & Pianese, C. (2019**). Generalized scaling-up approach based on Buckingham theorem for Polymer Electrolyte Membrane Fuel Cells impedance simulation**. *Energy Procedia*, *158*, 1514-1520. DOI: https://doi.org/10.1016/j.egypro.2019.01.360 (Open access)

Furthermore, to foster collaboration among partners and knowledge exchanges, one Master Student and 6 Bachelor Students were involved by UNISA. The master student experienced a training period at UFC. The details on the work done is available on the website of the project in the section Dissemination under the submenu exchanges (https://bit.ly/2GfU6XT). In the same section the list of the bachelor students and the topics dealt during their final work could be found.

4. Conclusions and Impact

The project HEALTH-CODE successfully achieved the envisaged objectives and delivered the expected results, providing methodologies, approaches and devices able to improve the monitoring and diagnostics of stationary PEMFCs.

The main achievements are listed below:

- Wide knowledge of PEMFC operations during the occurrence of six faults (fuel and oxidant starvation, drying and flooding, CO contamination and sulphur poisoning) which have been tested on O_2-H_2 and air-reformate gases for backup and μ-CHP systems, respectively.
- Large EIS database (more than 2300) acquired for single cell, short and full stack configurations.
- Validation of scaling-up algorithm for EIS analysis on single cell and short stack acquisition.
- Development of three diagnostic algorithms for the state-of-health of the stack and one additional algorithm for active diagnosis.
- Design, manufacturing, set-up and testing of power electronics for the integration with the EIS board into the μ-CHP system.
- Adaptation of existing power electronics for the integration of EIS board with backup system.
- Release of two prototypes of EIS board tool for the spectra acquisition and EIS data processing for on-line operation of the PEMFCs.

The activities performed within the HEALTH-CODE project were completed in time according to the scheduling and its objectives. The positive results obtained during the tests of the EIS board confirm the feasibility of the proposed methodology for on-board EIS measurements during real operations. The experimental campaigns were performed with real load applied to the two systems confirming the achievement of the TRL 6. Furthermore, the approach chosen for the monitoring and diagnostic tool proved its usefulness in detecting the six faults operation with high degree of accuracy. The flexibility of the approach and its generalizability are guaranteed by several techniques developed, which could be merged according to the implementation needs. The introduction of lifetime estimation algorithm based on state-of-health inference has shown the possibility of combining suitable diagnostic algorithm with performance/durability optimization strategies. As further remark, the implementation of a proper scaling-up technique confirmed the feasibility of performing experiments on SRU/single cell and extending these results to full stack, allowing the reduction of costs and time for experimental work.

The outcomes of HEALTH-CODE pave the way towards the implementation of EIS-based monitoring and diagnostics on commercial product after further engineering activities. Moreover, the availability of EIS spectra acquired while the system runs on field will facilitate the use of such a technique for lifetime (already tested in HEALTH-CODE), prognostics and advanced control of PEMFC. Additionally, perspective exploitation of advanced monitoring and diagnostics will lead to the improvement of maintenance actions and full integration within new energy paradigms such as smart building/grid as well as a useful implementation of Virtual Power Plant management concept.