ENhanced DURability materials for Advanced stacks of New solid oxide fuel CELls

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1. Publishable Summary (Mid-term review)

Project context and main objectives
In a sustainable future, fuel cells are considered one of the most effective and promising answers to the constantly increasing need of clean and reliable energy. These days long-faced discussions are held worldwide concerning solutions harmonizing exit strategies from the economical crisis, shortage of primary resources, and ecological and climate issues. Giving the fact that Energy is a key topic for both business and life to find a solution able to solve the intermittence of primary renewable power sources and to be flexible and adaptable to most of the applications despite their size, is a major positive aspect justifying the huge investment of human and capital resources into hydrogen driven power plants based on fuel cells. The Solid Oxide Fuel Cell (SOFC) is a consolidate system able to convert hydrogen and several kind of fuels (e.g. natural gas, biogas) into energy (i.e. electrical and heat power) with water as exhaust and, in case of carbon base fuels, very low CO₂ emissions (that can be used in carbon sequestration plant for the production of syn-gas).

The efficiency of the combined heat and power (CHP) systems integrating SOFCs can achieve efficiencies above 80% with a top-level electrical power efficiency of 60%. The focus of the ENDURANCE project is on the stacks mounting SOFCs with the aim to soundly contribute to their breakthrough marketing process by increasing their reliability and longevity without losing efficiency. In the nowadays scenario it is important to start from the state-of-the-art achievements of the scientific and industrial communities with the purpose of reinvest their knowledge for the sake of technology. For this reason the ENDURANCE consortium has a strong industrial core working in perfect balance and cooperative mood with the scientific partners with the common goal to solve the most urgent issues and then to introduce smart and simple solutions to increase the life span of the SOFC stacks. The main strategy to obtain such a challenging target is based on three pillars:

1) to improve the knowledge about the degradation mechanisms;
2) to refine the predictive models describing both cells and stacks life
3) to introduce an interactive system of Early Warning Output triggering counteractions to prevent failure or major damages.

In other words the ENDURANCE project aims at developing reliable predictive models to estimate in SOFC stacks: long-term (i.e. > 20 kh) performance, and probability of failure. To achieve these goals the "Macro to micro" approach has been applied to separate all single phenomena that are part of a real stack. These are then recombined to describe the "minima phenomena" defined by the essential interactions between materials, interfaces, components or parameters (e.g. temperature, load, fuel consumption, elements release) which are affecting each others’ behaviours. The available models can be then adapted, refined and combined in order to support the interpretation of the phenomena, to find the degradation sources, to predict their impact and to test the possible counteractions. In this way a stack becomes a device managing the counteractions (as far as it can) or "self-demanding" for maintenance before a failure is starting.
Extending the lifetime of a stack with a moderate and suitable degradation rate immediately transforms the initial cost of the SOFC based power system into an investment to be perceived not only as purely economical but also as ecological. This is most likely the main objective of the project.

**Work performed since the beginning of the project and main results achieved**

The goals of the project can be achieved by an increased awareness of the phenomena occurring inside a cell and in the whole set of the stack components during operation. The strategy consisted in a first Degradation Modes and Effect Analysis (DMEA) performing an extensive survey collecting data from literature and the experience of the involved partners reviewing as many components, assemblies, and subsystems as possible to identify degradation mechanisms and their causes and effects. Given the information provided by this analysis decisions were taken about the generation, distribution and characterization or testing of samples.

Samples have been designed in order to be representative of the most sensitive and meaningful parts of a real stack considering that all parts of the system are closely related and affecting each other. The related working conditions of each component have been chosen in order to simulate each sensitive part of the system and to obtain outputs suitable for feeding the thermomechanical and electrochemical models.

The modelling activity has been focused on the identification of complex phenomena, which have been consequently divided into single phenomenon more easily modelled and investigated. This simplification process was made with the highest awareness of strict dependency between single phenomenon. After the successful description of single steady state phenomenon an integration process is started to create a descriptive/predictive model for stacks. The models describing and predicting degradation rate deal with chemical composition of phases and interphases, alteration of microstructural characteristics, detrimental evolution of chemical, physical and mechanical properties. The first set of experimental results have been used to feed the electrochemical and thermomechanical models achieving higher resolutions and a more accurate predictability of the phenomena occurring at the stack level.

A first set of investigation has been performed on State of the Art operated stacks and samples aiming to refine the protocols, to find out the main issues on materials and their degradation behaviour confirming the previously described Degradation Modes and Effect Analysis outputs.

The comparison of such results with those obtained from segmented stacks tested in parallel during the first part of the project allowed to find out a close correlation between samples designed at different scales and the proper design to identify the degradation phenomena under investigation.

The developed and validated experimental approach allowed to achieve a deeper understanding of the degradation processes using small samples instead of full stack systems with a consequent resources optimization and the possibility to investigate a wider range of parameter which will enable a study on accelerated tests. Early Warning Output Signals are under investigation in order to identify evidences of degradation of the cells in an early stage and eventually take actions against such phenomena.

The dissemination was addressed, at the more technical and scientific level towards stakeholders (e.g. industries and researchers), and at the more widespread level to the community with the goal...
to increase the public awareness about fuel cells and hydrogen. In both cases the impact of the project achievements on the evolution of sustainable and safe energy was underlined. Young people, pupils, students and young researchers are an essential targeted group. For this reason in addition to the external web site, a special product (the Dissemination toolkit) has been urged as deliverable with long term impact having as a core the Serious Game named “The Lost Colony”. The first playable version has been developed and the promotion has been performed during the Festival of Science 2015 held in Genoa (Italy).

Stacking components characterization & improvement

Schematic view of the Macro to micro approach

Modelling (blue lines) vs. real measurements (grey lines) from a 3-cells short-stack. The differences of the two modelling curves are: (circles) simulations with several degradation phenomena implemented; (squares) predictions including a correction based on EIS analysis of a segmented-cell experiment.
The dissemination event "Festival of Science" held in Genoa (Italy) where the alpha version of the "Lost Colony" was played for the first time.

Expected final results and their potential impact and use

During the second half of the project the Improvement Iterative Loops will end with a list of results related to:

- Improved materials with lower loss in performances or sensitivity toward degradation sources
- Increased understanding of interaction and alteration phenomena within the stack and between materials and components
- Refined descriptive and predictive models
- Designed micro-samples representative of specific zones into the stack and able to switch from zone to zone in case of need by changing the ageing parameters
- Introduction of EWOS with related counteractions on the most sensitive parts of the stack (e.g. sealant, anode)

Coherently with the results achieved in the first half of the project the combination of suitably designed tests, Electrochemical Impedance Spectroscopy and post-experiment investigations have demonstrated the importance of EIS as main tool for monitoring the stack health state in real-time.

The third and last Loop dealing with statistical validation will give a final and complete picture of the progress made thanks to the project in the improvement of reliability and durability of the SOFC stacks issued by companies involved in the ENDURANCE.

From a technological and scientific point of view we expect as a final result a visible and sound contribution that paves the way on the market launching SOFC stacks as power sources tailored for various kind of applications. The related safety, security, and maintenance issues will be faced in a harmonized system where the majority of the possible failures are prevented or treated at their very early appearance with a mitigation of the harmful effect. This will widen the expectance of life and the predicted maintenance costs and reparation procedures. The increased reliability at stable or increased power density corresponds to a higher attractiveness of this product in several fields from stationary applications (e.g. from house-size to power plants stand alone or interfaced with other primary renewable energy sources) to mobile applications (e.g. on aircrafts or large ships).

A strong contribution will also emerge from the Dissemination and Exploitation activities where a clear and easy to pass message is given with a language adapted to the audience. The communication strategy is actually covering several fields from the more classical ones (e.g.
publication on scientific and peer-reviewed journals, participation to conferences, organization of workshops) to the more modern and mass media based ones (e.g. newspapers, radio interviews and broadcasting, computer serious game, public fairs on technology and large audience science festivals). At each event the local team in charge works to increase the public awareness about hydrogen and fuel cells, and to collect issues and requests in order to refine the communication strategy. The cross-fertilization with other activities related to the green economy are welcomed and stimulated, e.g. during the first part of the project a representative team of Endurance participated to the green mobility days in Lyon, organized by the FCH-JU, and to the Innovative mobility days in Genoa, organized by the EU project Electra. The serious game "The lost colony", based on an original plot written by a member of the consortium, is available on the website and distributed to schools (students 11-18 of age) where the players are demanded, in the final part of the game, to contribute by giving suggestions and original applications or solutions. The best among those received will be rewarded with an official document and a demonstrative kit. Moreover, the plot has been already at the origin of negotiations for further exploitations by media companies from outside the EU. It is therefore expected that at the end of the project the dissemination activity of the project will reach a very large audience contributing to the introduction and consolidation of the FUEL CELLS into Energy and Ecology challenges for a better future.