Final report

1.1 Project details

Project title	Solid Oxide Cell Testing, Safety and Quality Assurance
Project identification (program abbrev. and file)	EUDP 14-I. J.nr. 64014-0110
Name of the programme which has funded the project	Energiteknologisk Udviklings- og Demonstrations Program (EUDP).
Project managing company/institution (name and address)	DTU Energy, Frederiksborgvej 399, 4000 Roskilde
Project partners	DTU Energy *Partners in the European project:* DLR (coordinator, Germany), CEA (France), DTU (Denmark), ENEA (Italy), JRC (the Netherlands), EIFER (Germany) and NTU (Singapore).
CVR (central business register)	30 06 09 46
Date for submission	31-07-2017

1.2 Short description of project objective and results

DANSK
Testprocedurer er blevet udviklet til faststofoxid brændselsceller og elektrolyseceller (SOFC/SOEC) og -stakke. Procedurerne dækker relevante anvendelser: mikro-kraftvarmeanlæg, hjælpestrøm til lastbiler (APU), elektrolyseanlæg samt energilagringssystemer med reversibel SOFC-SOEC drift (power-to-gas-to-power). 11 mindre testmoduler er udarbejdet (f.eks. Opstart, Impedansspektroskopi og Drift ved kontant strøm). Disse er kombineret til 5 fulde testprogrammer til forskellige anvendelser. Alle moduler og programmer er eksperimentelt verificeret og forbedret gennem et antal iterationer.
Samarbejde med industrielle partere har sikret den industrielle relevans. Igangværende arbejde sikrer at testprocedurerne bliver implementeret i internationale standarder.
Projektet var en del af det europæiske forskningsprojekt, SOCTESQA.

ENGLISH:
Test procedures for solid oxide fuel cells and electrolysis cells (SOFC/SOEC) and stacks have been developed. The procedures cover relevant applications: micro-CHP, APU, electrolysis systems, and combined (reversible) systems (power-to-gas-to-power). 11 smaller test modules have been developed (e.g. Start-up, Electrochemical impedance spectroscopy, and Operation under constant current) and combined into 5 full test programmes targeting specific applications. All modules and programmes have been experimentally validated and improved through several iterations.
Interaction with an industrial advisory board has ensured industrial relevance. Work is ongoing implementing the test procedures in international standards.
The project was part of the EU research project SOCTESQA.

1.3 Executive summary

Both solid oxide fuel cells (SOFC) and solid oxide electrolysis cells (SOEC) will play important roles in the future energy system as technologies for balancing of the electricity grid. More and more fluctuating renewable sources (for example wind and solar energy) enter the European grids and new technologies replace conventional technologies in distributed generation and residential heat and power solutions (micro-combined heat and power, mCHP), such as diesel generators, natural gas or oil burners.

The EUDP project was an intergated part of the EU project, SOCTESQA. The project has developed uniform and industry wide test modules and programs for solid oxide cell and stack (SOC) assembly units. Relevant application have been addressed covering both operation of the SOC cell/stack in fuel cell mode (SOFC), electrolysis mode (SOEC), and in combined SOFC/SOEC mode. Energy conversion systems covered are stationary SOFC micro-CHP (combined heat and power), mobile SOFC APU (Auxiliary Power Units), stationary SOEC electrolyser systems (power-to-gas), and combined SOFC/SOEC (power-to-gas-to-power) energy storage systems.

All project partners were research institutes: DLR (coordinator, Germany), CEA (France), DTU (Denmark), ENEA (Italy), JRC (the Netherlands), EIFER (Germany) and NTU (Singapore). During the project, a close interaction with an industrial advisory board (IAB) ensured the industrial relevance of the project results. Additionally, a continuous liaison with standards developing organizations (SDOs) was established in order to successfully implement the outcome of the project into international standards.

Altogether 11 test modules were developed in the project, which are:
TM 00: General SOC testing guidelines,
TM 02: Start-up,
TM 03: Current-voltage characteristics,
TM 04: Electrochemical impedance spectroscopy,
TM 12: Operation under constant current,
TM 07: Reactant utilization,
TM 08: Reactant gas composition,
TM 09: Temperature sensitivity,
TM 13: Operation under varying current,
TM 14: Thermal cycling, and
TM 16: Shut-down.

These test modules were all experimentally validated by the project partners in several testing campaigns as well as the five full test programs (TPs) for the different applications.
All test modules are available from the project website: www.soctesqa.eu

For the development of the test modules several steps were performed. At the beginning of the project all important specifications, especially of the interfaces between the testing equipment (test stations) and test objects and the nomenclatures, were defined. For the validation of the test modules, short stacks with five repeating units from one selected SOC manufacturer were used. In the first testing campaign, the test stations were modified and harmonized in order to provide reliable and reproducible interfaces between the stacks and the test stations to achieve operating conditions as alike as possible between all partners and to follow dynamic profiles. In the following two testing campaigns, the test modules were validated and optimized with application-specific test programmes for SOFC, SOEC and combined SOFC/SOEC applications. In this context, technical input for the operating conditions of SOC systems from relevant industrial stakeholders were integrated in the test programmes.

The validation process mainly addressed the quality, reproducibility and repeatability of the results between the different partners and between the different test modules. The optimization of the test modules included thermal aspects like stack temperature, gas temperatures, temperature homogeneity inside the furnace, instabilities of the fuel gas humidification unit

and electrical wiring setup for electrochemical impedance spectroscopy (EIS). Additionally, aspects for the reproducible determination of degradation rates were implemented in the long-term operation test modules. Moreover, recommendations for the reliable calculation of derived quantities, e.g. area-specific resistance (ASR), reactant utilizations and low and high frequency resistances, were included in the test modules. At the end of the project, a final round robin test was performed, which showed feasible application of the modules through high quality results with good reproducibility and repeatability at the different test laboratories of the partners. Hence, the robustness of the optimized test modules was confirmed.

The exploitation of the project mainly focused on the transfer of the results to standards developing organizations, e.g. the International Electrotechnical Commission (IEC) and CEN/CENELEC, the main European standards developing organisations in the field. A formal liaison of the SOCTESQA consortium with both entities was established. In case of IEC, a new working group (WG 13) was initiated within the Technical Committee "Fuel cell technologies" (TC105). The entire SOCTESQA consortium participated in and guided the activities, leading to the definition of the current draft of Standard 62282-8-101, expected to be published in 2018: "Energy storage systems using fuel cell modules in reverse mode - Test procedures for solid oxide single cell and stack performance including operation in reverse mode".

Moreover, the project results have been broadly disseminated to general and scientific public, e.g. by five scientific papers, and a number of conference contributions, workshops, fairs and the SOCTESQA website (http://www.soctesqa.eu). In this way the maximum exploitation was achieved, creating worldwide discussion and awareness of the topic.

1.4 Project objectives and the implementation of the project

Project objectives

The purpose of the project was to develop and validate a full set of industry relevant test procedures for solid oxide cells operating in different modes (e.g. SOFC, SOEC and combined SOFC/SOEC), addressing function, performance, durability and degradation. Each of these cases includes both steady state and dynamic operation in order to cover many potential applications. The aim was to provide robust and easy-to-use protocols for experimental characterization and interpretation of measured data.

How did the project evolve?

The objectives have been fully achieved in the project and results have been well disseminated and implementation of results have been on-going since quite early in the project.
In the beginning of the project, there was delay. It took longer time than expected to select the provider of the test objects (SOC manufacturer) and also the delivery time was longer.
The project caught up with the delay through clever organising of the test matrix between the partners and continued follow-up on the time schedule.
Some partners had troubles preparing the interface between the stack and the test station, and the less experience partners had problems getting steady operation and useful test results.
The cooperation between partners was very good with exchange of knowledge on testing issues and best practice.
In the end, DTU carried out extra tests to make up for delay and missing test capacity at other project partners. As the only project partner, DTU was able to make successful testing of all 7 stacks provided in the project, i.e. a test success rate of 100%.

Did the project implementation develop as foreseen and according to milestones agreed upon?

Besides the initial delay, the project developed according to the plan. All milestones have been reached. The commercial milestone CM 7.1 "Project progress workshop with SDO

and IAB" was achieved in December 2015 in Napoli as part of a conference. There was fine attendance of key stakeholders and important exchange of information took place.

1.5 Project results and dissemination of results

Project results

Overview of already existing test standards and other relevant documents was prepared early in the project.
Detailed requirements and specifications the for test specimen were made and a provider of SOC small stacks were selected.
Approximately 49 small SOFC stacks were tested through 4 testing campaigns at the 7 project partners' test laboratories.
11 test modules have been developed and 5 testing programmes, covering the applications aimed for in the objectives. All modules and programmes have been varified experimentally and improved through a number of iterations.
Guidelines for how to make SOFC/SOEC testing of high quality have been developed in the so-called TM 00 document.
Interaction with industry has taken place throughout the project.
A work on implementation of the project results in international standards have been going on for now 2 years. The most important result regarding implementation is the establishment of a new working group in the International Electrotechnical Commission (IEC). The aim is specifically to implement the results by issuing a new standard (62282-8-101) "Energy storage systems using fuel cell modules in reverse mode - Test procedures for solid oxide single cell and stack performance including operation in reverse mode", presently available as a draft, but expected to be published in 2018.

Dissemination of results

All reports and test modules are available on the project website: http://www.soctesqa.eu/

DTU has been active in dissemination of project results, both in Denmark and internationally.

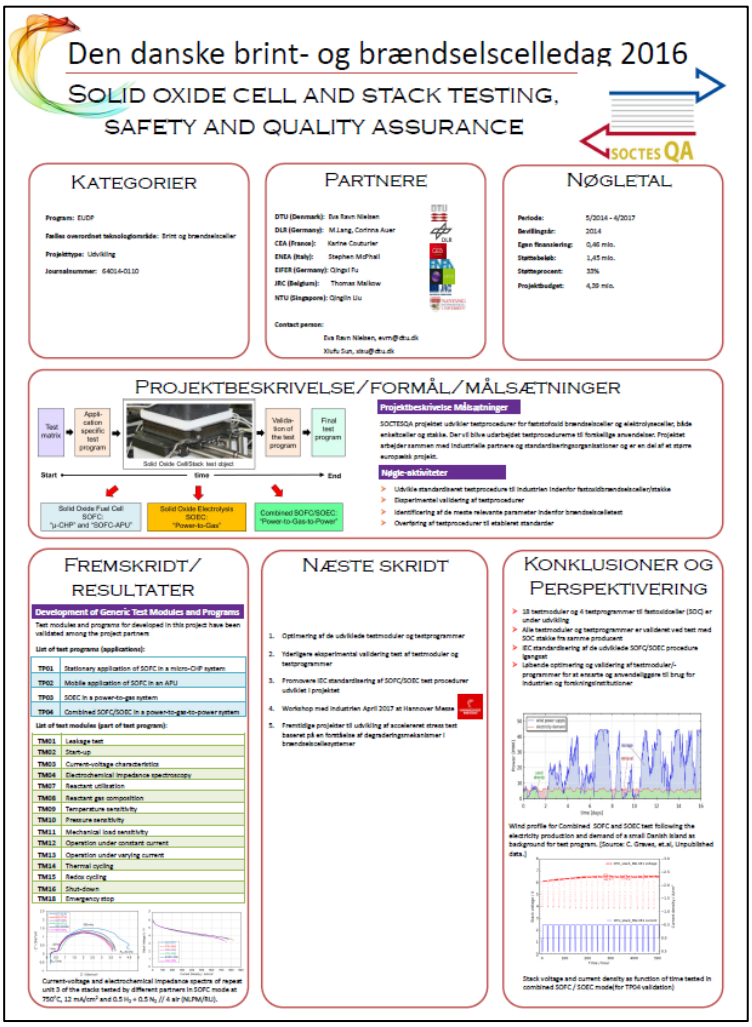
- Hannover Messe 2015, 2016 and 2017
- Den danske brint- og brændselscelledag 2016
- Gastekniske dage, 2016
- Presentation to Danish Standard, S-605 Committe on Hydrogen and Fuel Cells
- Presentation to IDA Energi, February 2017: Det sidst nye inden for bioenergi, brint og brændselsceller.

Several presentations internally at DTU Energy, which besides Haldor Topsøe A/S is the place in Denmark to actually implement and utilize the new test procedures. Following the closing of Topsoe Fuel Cell, Haldor Topsøe A/S unfertunately decided not to take part in the SOCTESQA industrial advisory board.

Below documentation of various presentations and links have been given.

Final SOCTESQA dissemination event, Hannover Messe 2017:
See the full presentation on YouTube: https://www.youtube.com/watch?v=eDiFcqGpdII

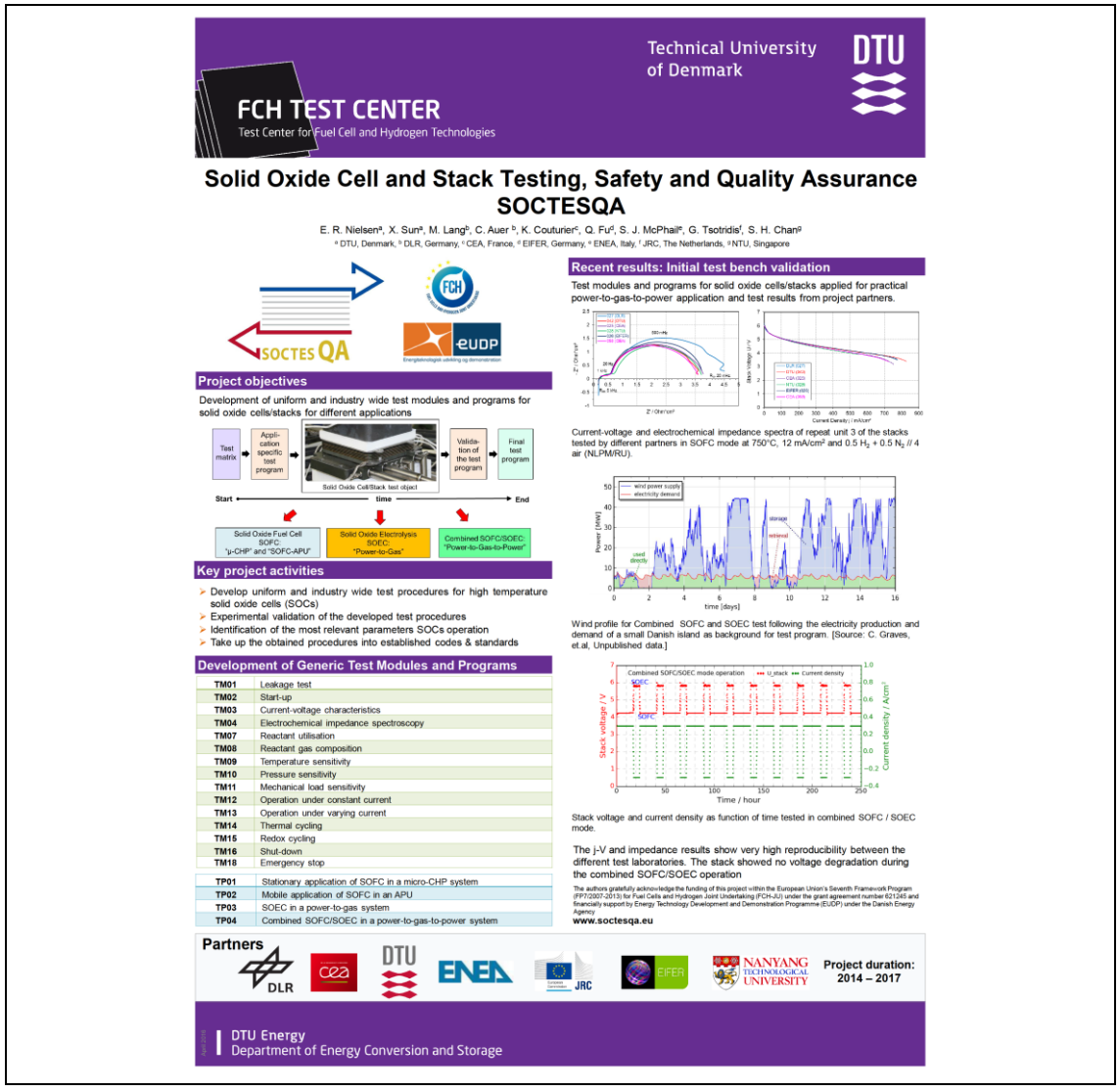
Poster was presented in November 2016 in Odense at Den danske brint- og brændselscelle-dag:



Dissemination of SOCTESQA results at Hannover Messe 2016

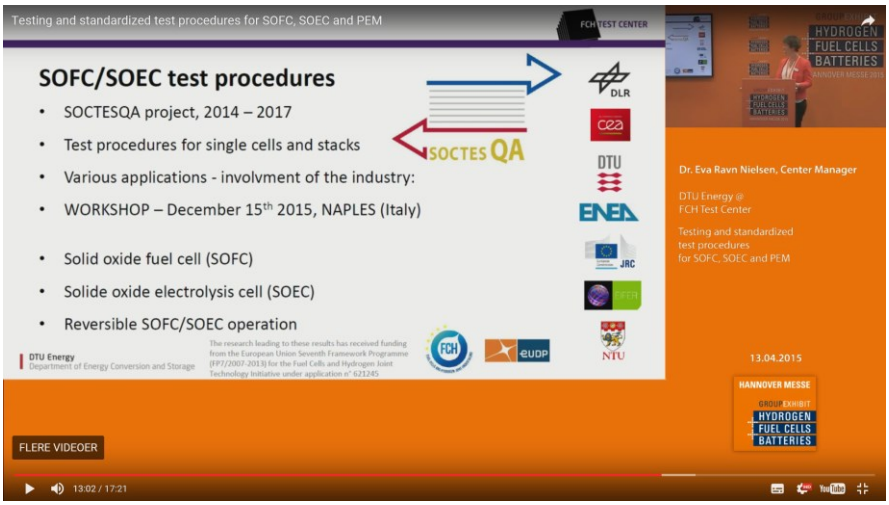
DTU booth picture with posters in the background, Hannover Messe 2016:

SOCTESQA poster presented, Hannover Messe 2016:



Presentation from DTU, Hannover 2016:
On Youtube: https://www.youtube.com/watch?v=KUCRQkR7VjM

Presentation, Hannover 2015:
On YouTube: https://www.youtube.com/watch?v=UtBey7_sl7A



1.6 Utilization of project results

The SOCTESQA project is of pre-normative nature but still essential for the market penetration of solid oxide based technologies. This as relevant and rigid test procedures will enable cell and stack manufacturers as well as system integrators to make true and fair comparisons between different systems, ease the integration of new components and thereby improve the product development. These are essential factor for large scale commercialization of solid oxide (SOC) based products to take place.

The developed test procedures do, in contrast to previous projects, include not only steady state operation, but also dynamic operating conditions as well as advanced and well established characterization techniques (e.g. electrochemical impedance spectroscopy).

The most important utilization of results is the on-going work on implementing the developed test procedures in international standards (IEC 62282-8-101).

However, the actual implementation of the test procedures in on-going test activities and projects is a fast result proving the relevance and usefulness of the outcome. The SOCTESQA tests procedures have already been integrated in the Danish EUDP project Maturing SOEC, The German project SMART 2, and the EU projects BALANCE and ECo. And naturally, the test procedures are now the basis in the test laboratories of the project partners and a number of stakeholders.

1.7 Project conclusion and perspective

The project, including the EU project, has been very successful in developing application specific and industrial relevant test procedures for SOFC and SOEC. The results are already widely implemented at testing laboratories and as the basis for testing in national and international projects. Work is in fine progress to integrate the new test procedures in international standards.

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Test procedures for solid oxide fuel cells and electrolysis cells (SOFC/SOEC) and stacks have been developed. The procedures cover relevant applications: micro-CHP, APU, electrolysis systems, and combined (reversible) systems (power-to-gas-to-power). 11 smaller test modules have been developed (e.g. Start-up, Electrochemical impedance spectroscopy, and Operation under constant current) and combined into 5 full test programmes targeting specific applications. All modules and programmes have been experimentally validated and improved through several iterations.

The purpose of the project was to develop and validate a full set of industry relevant test procedures for solid oxide cells operating in different modes (e.g. SOFC, SOEC and combined SOFC/SOEC), addressing function, performance, durability and degradation. Each of these cases includes both steady state and dynamic operation in order to cover many potential applications. The aim was to provide robust and easy-to-use protocols for experimental characterization and interpretation of measured data.

This purpose have been met by the project, and the immediate need for test procedures for SOFC/SOEC cells and stacks have been covered. Future new applications of SOFC/SOEC or new characterization methods may course a new need for supplementing test procedures, but it is not foreseen on short term. However, there might be a corresponding need for specific test procedures for testing on system level, now and in the future. It is likely that this topic will be addressed by the Fuel Cell and Hydrogen Joint Undertaking in future calls for project applications, as it was done on cell and stack level resulting in the SOCTESQA project.

Even though the implementation of the project results already has come far, all project partners should continue to share information and experience regarding the new test procedures and standards in the fuel cell and hydrogen community.

Annex

All test modules are available from the project website: www.soctesqa.eu