DEMOSOFC

Project n° 671470

"DEMOnstration of large SOFC system fed with biogas from WWTP"

Deliverable number 3.2

Installation of the DEMO

Due Date of Delivery:	M20
Actual Submission Date:	28/01/2021
Lead Beneficiary:	Convion
Author(s):	Tuomas Hakala, Toni Ollikainen, Jukka Kunnas (CONVION)
	Marta Gandiglio, Andrea Lanzini, Massimo Santarelli (POLITO)
Approved by:	Massimo Santarelli (POLITO)
Work package:	WP3
Dissemination Level:	PU
Nature:	R
Version:	1
Total number of pages:	18

Abstract:

The deliverable aims to describe the installation procedure for the DEMOSOFC plant (SOFC module 1 and 2), including the documentation issued, the testing procedures and acceptance tests, and the shipment to the site.

Keyword list:

SOFC, fuel cell, installation, biogas, documentation, testing, FAT, SAT

Summary

Introduction

The primary purpose of the DEMOSOFC project is a functional installation of a biogas fuelled SOFC power plant integrated in a wastewater treatment application. The work constitutes of the planning and engineering of the integrated local energy concept and construction of the site with all of the auxiliaries needed for the main function, CHP generation by fuel cells using locally produced biogas fuel. At the core of the concept are 2 SOFC modules (around 50 kW each) provided by Convion. Already prior to the project, SMAT Collegno wastewater treatment plant had anaerobic digestion plant for production of biogas and a boiler for utilization of the produced biogas for thermal needs of the process. The aim of the project was to plan and carry out a revamping of the system so that energy content of the produced biogas could be used more completely in a CHP system.

Application of anaerobic digestion in wastewater treatment is common in large facilities but due to inefficiency and prohibitively costly maintenance of conventional generation technologies in small scale, adoption of anaerobic digestion and on-site CHP is low in a power range of hundreds of kilowatts. Since SOFC fuel cell technology is modular and its performance is not only highest among all technologies but also independent of scale, it has a lot of new market potential. The DEMOSOFC project demonstrates a replicable, engineered reference installation of SOFC CHP in a wastewater application. As the installation is *first-of-its-kind*, the process by which the installation is managed and executed provides invaluable experiences regarding a plethora of practical, regulatory and communication issues for all parties involved and provides the necessary means of standardizing solutions and practices.

This document outlines the installation site and environmental requirements and system interfaces as well as safety engineering principles and designed compliance of directives.

1. DEMOSOFC plant interfaces

Convion C50 is a standardized and modular SOFC power plant. It is a fully equipped system capable of combined heat and power generation and it can be configured for operating with different fuel gas compositions such as natural gas or biogas. Modular architecture makes possible installation of multiple C50 units in parallel for desired level of power output and redundancy and gradually extending the capacity by one module at a time – provided that the site is designed and can be equipped for the extension. Illustration of the site design with all of the interfacing auxiliary systems is in *Figure 1*.

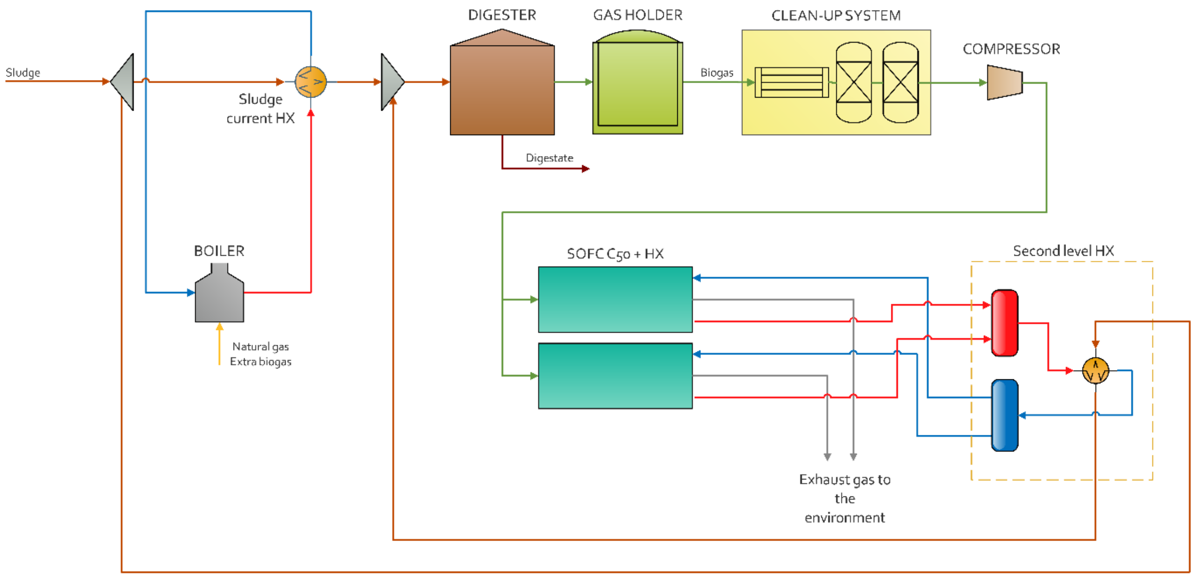

Figure 1. DEMOSOFC plant scheme.

Excluded from the standard module are the scalable and customized parts of the installation – gas clean-up and pressurization when needed as well as the receiving end of the heat recovery system and grid connecting contactors, which are specific to installation size and grid codes. Each module is a separate generator, able to operate independently and autonomously, yet connected for remote management and monitoring and operable as a single entity. The SOFC module is designed to be installed parallel to the power grid but it is capable of disconnecting from the grid and securing critical power loads in case of a grid outage. Redundancy and dynamicity of the industrial micro grid can be enhanced with a suitably sized energy storage, as is the case in the DEMOSOFC installation. Figure 2 illustrates schematically what belongs to the standard and parallelized SOFC system and how it interfaces with the auxiliary installation.

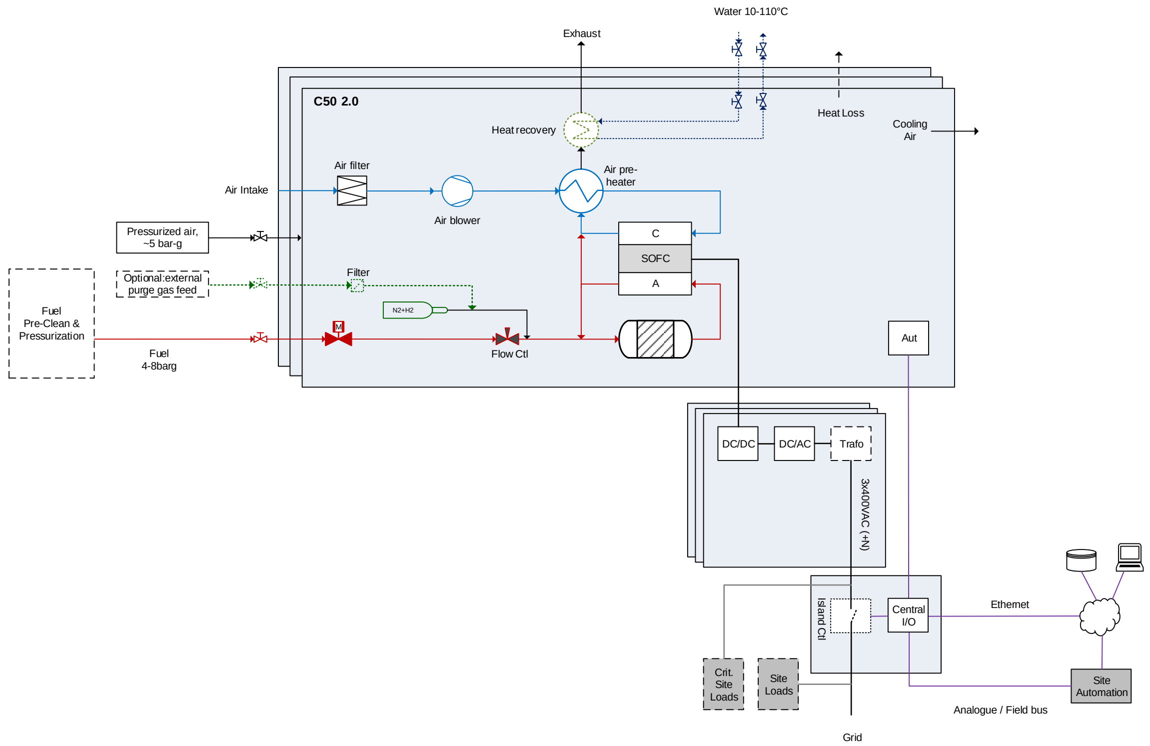

Figure 2. Constituents of the standardized and modular SOFC systems highlighted with the light grey background. Auxiliaries external to the modules can be customized and scalable.

A standard C50 fuel cell unit consists of a stack module as well as process, automation and power conversion modules for facilitating power generation from the unit. At the C50 module interface, pre-cleaned and pressurized fuel and clean, pressurized air is required. Humidity of both fuel and pressurized air must be managed to ensure non-condensing conditions at system interface at all times. Process air is taken in by C50 at ambient pressure. A heat exchanger for exhaust heat recovery is installed inside the C50 product and connected to the

Table 1. General specification of the SOFC module.

C50 General specification	
Fuel	Natural gas or biogas
Nominal AC power [kWe]	58
Electrical efficiency [%-LHV]	> 53
Exhaust temperature @ rated power [°C]	222
Exhaust flow rate @ rated power [kg/h]	650
Specific heat capacity [J/kg, K]	1072
Allowed back pressure [mbar]	25
CHP capability	Optional
Overall efficiency (CHP @60C), %	> 80
Noise level (dB(A) at 1 m)	< 70
Island mode operation	Optional

1.1 Power connection

C50 unit can be connected to the power grid acc. to IEC61800-3 standard and local grid codes. Electrical connection is characterized in *Table 2* below.

Table 2. Power connection.

POWER CONNECTION	C50
Electrical connection, capability	3x380-440V AC 50/60Hz
Grid current, apparent [A]	105
EMC emission level	2nd environment - Power drive system of category C3 - I > 100A, (IEC 61800-3)
Electrical connection [Vac]	380…440
Grid current, active [A]	88…76
Grid current, reactive [A]	57…72
Apparent power [kVA]	69…80
Reactive power [kVar]	38…55
Surge protective device	1.5 kV prot., Type 2 for IT 400 / 690 V grids
Current THD, [%]	< 4
Operation in grid failure situations	Fault ride-through
Island operation (optional)	Island capable, 1 second power outage in islanding
Maximum cabling distance from Process unit to Power conditioning cabinet [m]	30
Protection of power conditioning cabinets	IP52 (indoors)

There are two requirements for the circuitry of grid connecting contactors of C50 fuel cell systems. First, signal for controls of grid connecting contactors should be brought to PLC of C50 fuel cell systems. Second, a circuit that lags reconnection of grid contactors by a delay defined in C50 PLC. *Figure 3* below illustrates the grid interface with grid connecting contactors, grid protection relay, signal interface between the grid protection relay and PLC, and mains circuitry of SOFC unit and its auxiliaries.

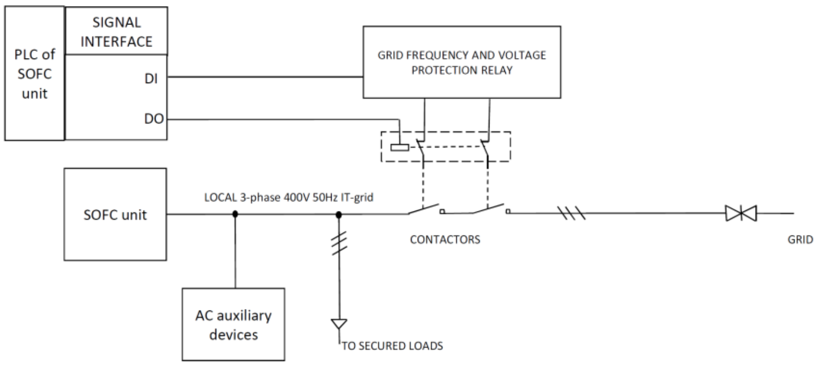

Figure 3. Grid interface.

1.2 Fuel and air supply interfaces

Table 3 summarizes fuel quality envelope and target maximum levels of specific impurity concentrations. Cleaning shall be carried out with methods selective and specific enough to facilitate predictable results and maintenance intervals.

Table 3. Summary of fuel and air quality requirements.

Fuel	
Pressure [bar-g]	4 bar-g +/- 0.2
NG / BG Composition	
Methane, CH_4 [%-mol]	55...100
Ethane, C_2H_6 [%-mol]	0...7
Propane, C_3H_8 [%-mol]	0...4
Butane, C_4H_{10} [%-mol]	0…1
Carbon dioxide, CO_2 [%-mol]	0…45
Oxygen, O_2 [%-mol]	0...1
Nitrogen, N_2 [%-mol]	0…45
LHV J/kmol @ 25°C	441-850
Temperature [°C]	-10-+40
Fuel Impurities	
Max sulphur content at system inlet	< 30ppb i.e. <0.04 mg(S)/m3 of total sulphur (originating from H_2S, COS, THT, DMS etc.)
Max silicon (siloxanes) content at system inlet	< 0.06 mg(Si)/m3 (corresponds to ~10 ppb or 0.16 mg/m3 of D5 siloxane)
Halogen compounds [ppm]	< 1 ppm total, (e.g. Cl_2, HCl, halogenated hydrocarbons)
Allowed level of humidity	Non-condensing @ ambient temperature and fuel pressure
Air	
Air quality	Ambient air*
Temperature [°C]	-20 - +40
Pressurized air	
Pressure [bar-g]	≥4 bar-g
Temperature [°C]	-10 – +40

1.3 Heat recovery connection

The C50 modules for the DEMOSOFC installation are equipped with optional heat recovery heat exchangers which are installed inside the C50 power units. Cold and hot water connections are available in the unit for connecting the internal C50 HEX with the site heat recovery loop.

2. Documentation and compliance

The DEMOSOFC installation is a first installation of the C50 product outside of Convion test facility premises. Therefore, plant engineering and design has been an iterative effort with the project partners and the project has provided a fruitful test bed for technical communications. The C50 product was provided with following documentation

- Operational manual
- Service manual
- Installation manual

Additionally, technical meetings, reviews and correspondence have ensured correct implementation of the installation requirements. Final installation and acceptance of all SOFC interfacing auxiliary systems has been checked and approved by a person trained and authorized by Convion.

Authorization for the realization and the operation of an experimental SOFC plant in the SMAT S.p.A WWTP of Collegno is conditional to safe engineering and appropriate standards compliance.

Convion C50 has been designed to fulfil requirements of the following applicable directives:

- Machinery Directive 2006/42/EC,
- EMC Directive 2014/30/EU,

And based on the applicable standards

- Stationary fuel cell power systems – Safety IEC 62282-3-100
- Stationary fuel cell power systems - Performance test methods IEC 62282-3-200
- Stationary fuel cell power systems – Installation IEC 62282-3-300
- Safety of machinery - Basic concepts, general principles for design. SFS-EN ISO 12100
- Adjustable speed electrical power drive systems –Part 3: EMC requirements and specific test methods IEC 61800-3
- Safety of machinery - Electrical equipment of machines - Part 1: General requirements EN 60204-1

3. Convion Safety and Quality Assurance Process

Assuring the safety of products is the highest priority in all operations at Convion. The guiding principle is risk avoidance. In addition to safety, high quality and reliability are defining targets for design, manufacturing and operation and same principles apply as for safety. Product safety and safety in operations must be inherent, not relying solely on vigilance during manufacturing and personnel. Failures in individual system components must not compromise safety and any foreseeable failure in an individual component must not cause escalating damage to the whole product. For quality improvement and future safety reviews, proper documentation and records are maintained at all stages of sourcing, manufacturing and testing of the product.

The primary methods for identifying safety and reliability related risks are Hazard and Operability Analysis (HAZOP) and Failure Mode, Effect and Criticality Analysis (FMECA). These methods are initially applied in the early design phase of a product and updated at later stages. With respect to safety, essential risk mechanisms are explosion risks, risks associated with high temperatures, risks related to pressure (i.e. mechanical integrity of fluid conveying structures) and electrical risks. For gas conveying equipment HAZOP is used as a systematic approach to identify abnormal situations, their possible causes and consequences. FMECA is used e.g. for ventilation and electrical systems where a device failure mode-oriented approach is more suitable. Identified risks are recorded as action points for e.g. design, sourcing and/or commissioning.

The first priority of the system gas safety design is to eliminate explosion risk and mitigation of fire safety and explosion risk starts at the very concept of the product. Within the fuel cell system

enclosure, conveying and processing of combustible species is limited to a process module and a stack module. The process module consists of a cold area and a hot area separated by an insulation wall with openings for ventilation flow. The free air volume in both areas is <=1m3. An EX-rated suction blower is situated in the top of the hot area facilitating a ventilation flow >=100m3 through the process module. Ambient air enters in the cold end through a dust filter, first flows through cold area and thereafter flows through the hot area. For the purpose of gas leakage detection, a gas indicator monitors the combustible content of the ventilation gas at the suction blower. The presence of a proper negative pressure inside the process module is monitored by a differential pressure sensor positioned over the ventilation air inlet filter.
As the ventilation flow heats up in the hot end it is cooled down by ambient air in an air-air heat exchanger prior to the gas indicator and suction blower. A blower additionally facilitates an internal circulation of cooling air in the hot area. Similarly, in the cold area there is an internal “closed loop” cooling through an air-air heat exchanger.
Minimization of the risk of explosion relies on the following principles

- High rate and availability of ventilation
- Gas detection
- Operation above self-ignition point
- Shut-off gas supply
- De-energization of non-EX equipment

In case an emergency shut down is triggered by a gas sensor, manual press of an emergency shut-off button or a signal from plant automation, fuel feed is stopped and pipelines and vessels containing combustible gases are flushed with N2, DC/DC converters are shut down and the fuel cell unit is shut down by means of safety relays
C50 consumes pressurized fuel and air. In terms of standards compliance, based on pressure, types of gases and diameters and volume of piping conveying gases a pressure, all pipework fall under category SEP (sound engineering practice, as defined in Pressure Equipment Directive 2014/68/EU) based on pressure equipment hazard assessment. A different category assessment may apply to gas cleaning system and purge gas storage, which, while connected to C50 in an installation, are external systems and not within the scope of the C50.
The C50 SOFC modules shall not be placed to operate in an ATEX regulated.

4. Factory Acceptance Testing

Convion’s fuel cell systems are built up of modules that are produced separately by Convion’s suppliers. All modules must pass a predefined Factory Acceptance Test (FAT) for quality and compliance assurance. The supplier carries out and compiles a report on the FAT. The FAT comprises the following actions/measurements

- Check that that design is in accordance with latest drawings
- Process diagram check, valves etc. installed in proper direction
- Leak or pressure test.
- Critical dimensions check
- Photographing of interior of pipes (cleanness)
- For painted parts, measurement of paint layer thickness
- Electrical checks (wiring check, isolation resistance, etc.)

Acceptance criteria for each test have been defined by Convion and measurements and required logs depend on the module or assembly to be tested. In case the criteria are not met, corrective actions must be taken, and tests remade until the results are approved by Convion. Prior to main assembly of the modules to the system, essential tests (e.g. tightness) are remade by Convion. At every stage, a solid trace of documents and records according to acceptance criteria are produced and archived for further review.

5. Software Safety and Reliability

Convion's fuel cell systems involve sophisticated control and diagnostics algorithms, implemented on an industrial programmable logic controller (PLC). The software engineering follows a lean approach for failure avoidance. However, due to the nature of the control it is nevertheless necessary to be able to update the code during the pilot phase. As the system cannot be easily shut down and rebooted, updates to the control logic need to be made online while the system is operating. Online modifications are only done with precaution and on limited code sections by Convion automation experts. To avoid safety reliance on the PLC and its code, critical safety functions have been implemented using a hardwired safety circuit that is independent of the PLC. The hardwired safety circuit also includes a watchdog for the PLC.
Prior to operating a system, the proper functionality of PLC code is validated by operating the logic on a proprietary real-time dynamic process model that emulates all process components and IO signals. The human-machine interface (HMI) is also tested in the same arrangement. The model can also be used to validate code updates prior to making corresponding modifications to running systems.

6. Test Readiness Review

A key step of safety and quality assessment if the Test Readiness Review (TRR), which is carried out before any combustible fuels are let into a new system. The TRR involves the following checkpoints

6.1 Documentation Review

Check that all relevant documentation exists

- PI-diagram, system and application
- IO-list and circuit diagrams
- Component specifications
- Material and chemical safety data
- Electrical drawings
- Cable list
- Control Specification
- Alarm List
- Safety Specification
- FAT reports
- Calibration certificates
- Electrical measurement log

6.2 Review of Modifications

If any changes have been made after previous reviews, check that all relevant documentation is updated. In particular verify that

- Changes are according to design
- Change request log has been reviewed and updated
- Risk and defect log has been reviewed and updated

- Required Leak tests have been done
- Required electrical measurements have been done

6.3 Control System Review

To assure the proper function of the control system is reviewed that the following actions have been carried out and documented properly

- Signal and channel has been made and documented
- All hardwired safety devices and procedures have been tested
- Component functionality tests have been done
- Control functions tested (with simulator on and/or in the system)
- HMI has been tested and verified that all instrumentation values can be accessed
- Data logging and event logging functionality has been verified
- Remote operability has been verified
- All HAZOP issues have been checked and implemented

6.4 Installation Site Review

- Are all required site safety devices (gas, fire sensors etc) tested
- Is the ventilation sufficient
- Emergency stop buttons accessible and functional
- Gas closing valves accessible and functional
- Has all site piping been properly pressure tested
- Are all necessary fluids and consumables available
- Are all electrical connections and signals functional
- Are all personnel operating the system properly trained

6.5 Final Assessment

Based on the checklists it is assessed whether the unit can be safely started/delivered. In case only minor actions are needed before starting, the start approval can be given with remarks, whereby said actions need to be handled and verified prior to start. In case of major deviations or unresolved safety issues, the test readiness review is disapproved and has to redone in completeness after corrective actions have been taken.

Once test readiness approval has been obtained, the system is tested according to a test plan. For new designs, a type test is carried out to verify the functionality, whereas for repeated designs, only a more limited routine test is required. Type tests include control logic and overall operability verification, performance and emission measurements and special condition tests (e.g. island model operability). Type and routine tests are short duration only and do not measure e.g. degradation. The testing can be made at Convion's facilities or at another approved site.

7. Laboratory validation

For verification purposes and partial compliance of appropriate standards a laboratory validation of the unit was carried out before shipment of the unit the final installation site. Measurement requirements of the fuel cell standards (IEC 62282-3-100 -200- 300) were fulfilled by external characterization equipment (e.g. energy metering, emissions, fuel metering) at the test boundary as illustrated in *Figure 4*.

IEC 62282 covers operational and environmental aspects of the stationary fuel cell power systems performance. The test methods apply as follows:

- power output under specified operating and transient conditions;
- electric and thermal efficiency under specified operating conditions;
- environmental characteristics; for example, gas emissions, noise, etc. under specified
- operating and transient conditions.

All energy recovery systems are included within the test boundary and calculation of the heating value of the input fuel is based on the conditions of the fuel at the boundary of the fuel cell power system. Results of the tests will be covered in more detail, together with long term operational data at the site in a technical deliverable.

In order to emulate biogas operation an arrangement (*Figure 5*) of supplying a controlled gas mixture with representative calorific value was used. In the arrangement natural gas (~98% CH_4 in Finland) with known composition and calorific value was blended with CO_2 and N_2 at appropriate dilution rates to produce a mixture representing biogas at the SMAT Collegno site.

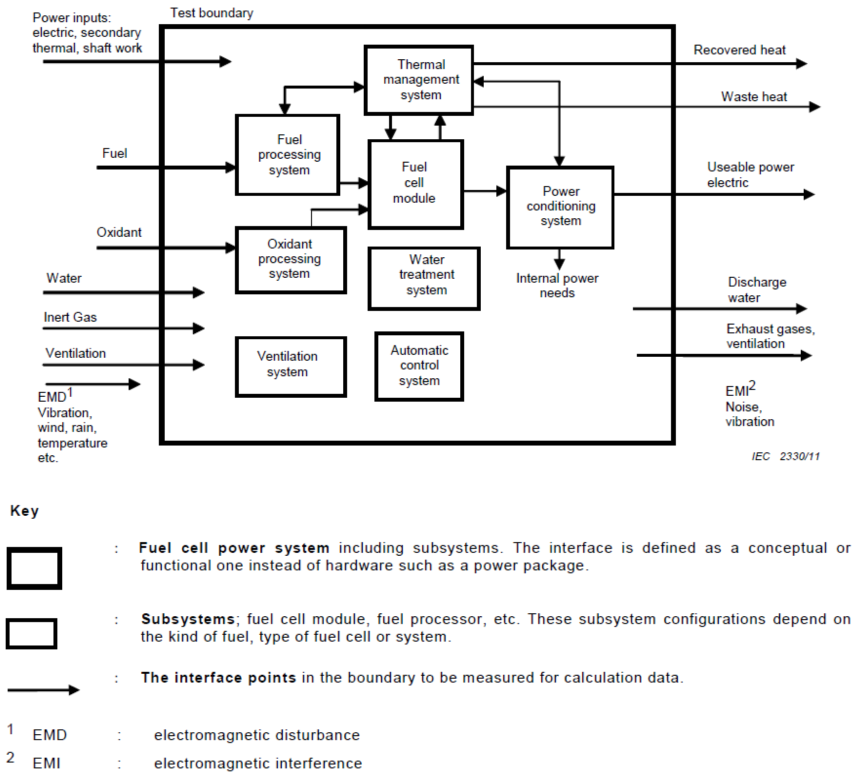

Figure 4. Fuel cell power system diagram and the test boundary as defined by IEC 62282-3-100/ 200/ 300.

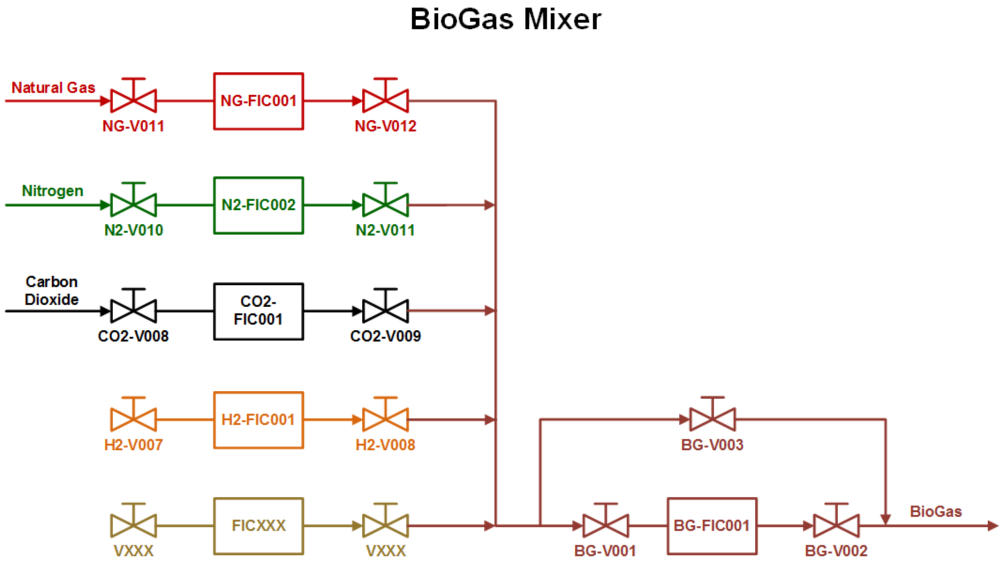

Figure 5. Arrangement for supplying controlled gas mixture of a given calorific value.

C50 conformity assessment procedure demonstrates compliance of C50 with the technical requirements of the directives and on passing the relevant type tests specified in the fuel cell standards. The test campaign for the EMC compliance is based on the standard IEC 61800-3. To reach the compliance of the EMI levels, a test campaign has to be passed on the 3 first units. Pre-compliance EMI tests have been run on a prototype but, final assessment will be carried out on the course of the project.

Performance and characterization test results will be discussed in further detail in the technical deliverable documents. At-a-glance results of operating the unit for >1000h at Convion premises are shown below in *Figure 8* - *Figure 7* for SOFC1.

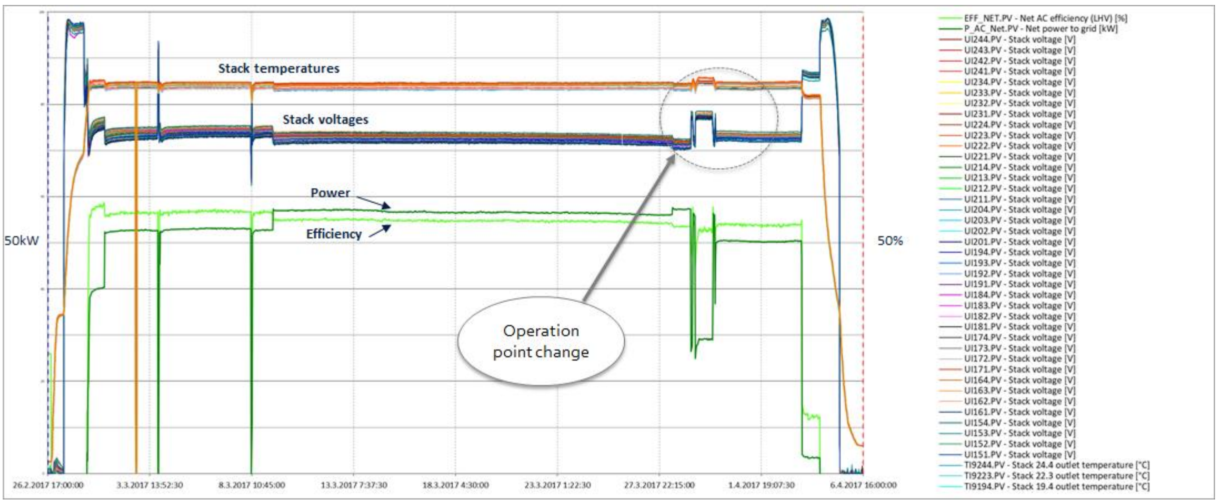

Figure 6. A test run of >1000 hours including different operation points and fuel compositions (SOFC1).

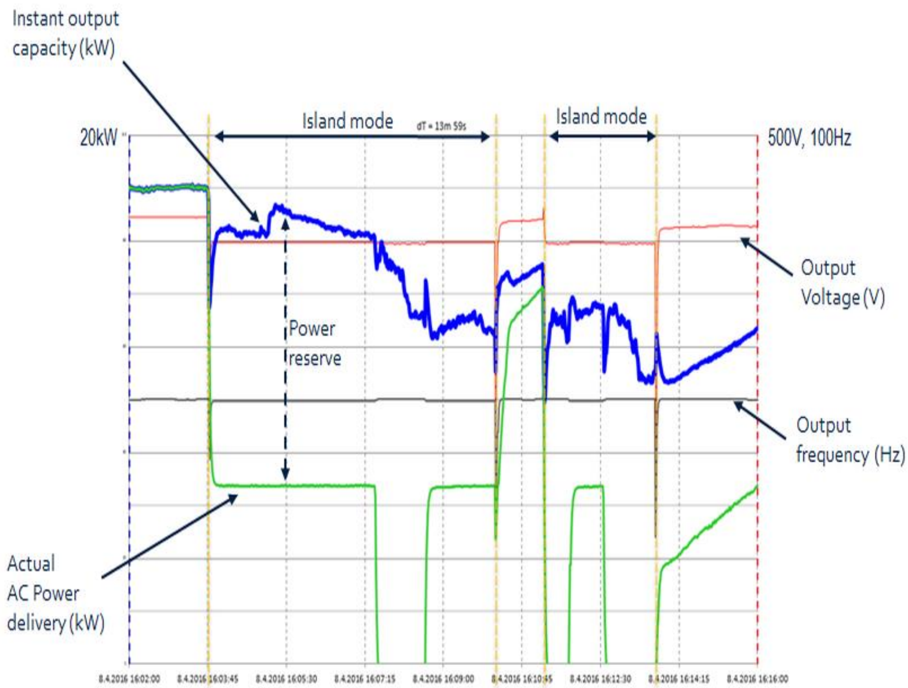

Figure 7. Tests of the grid forming/ load following capability of the SOFC in an intended island during an emulated grid outage (SOFC1).

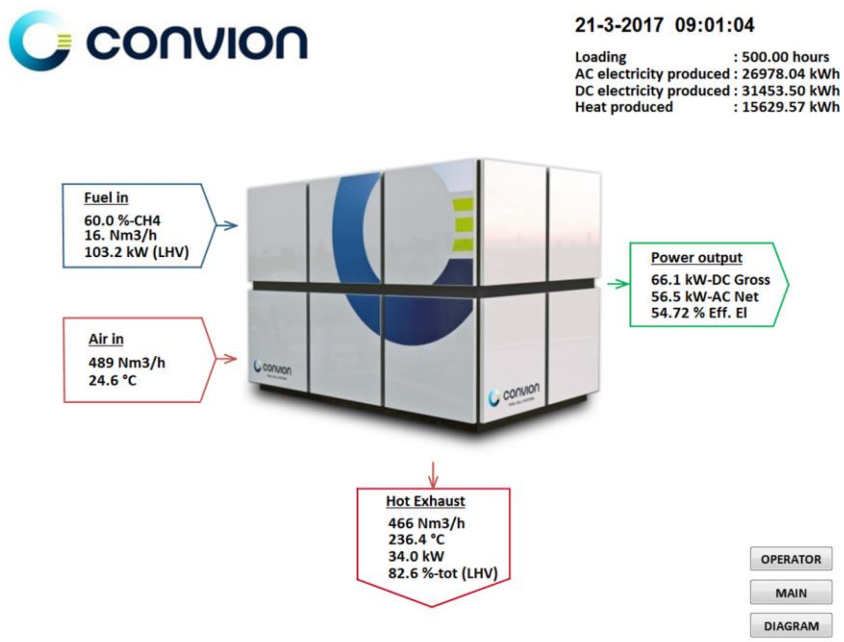

Figure 8. Operating display of the C50 during the emulated biogas validation tests in a laboratory (SOFC1).

8. Performance over time

A fuel cell systems performance over time depends on stack performance. Characteristic to SOFC stacks is a gradual decline in voltage over time. There are a number of factors affecting the rate of stack degradation, some of which are related to the material combinations, processing and typical quality of production of cells and stacks but additionally, e.g. operating principle in a given process scheme, actual operating conditions resulting from the integration to the system, load profile, quality of fuel and impurities in fuel and air all have an effect on rate of degradation. Since the rate of degradation define a useful lifetime of a given stack as well as average performance, the figure of voltage degradation is of great interest. For a system manufacturer, it is essential that the system can maximally capture the performance and lifetime potential that is built into the stacks but the system tests, particularly short term validation tests with a lot of different objectives to be fulfilled and, consequently, various thermal events and transients as well as e.g. varying fuel compositions, do not produce generalizable degradation information. Baseline for the degradation must be measured with an appropriately large set of stacks representing the type and design in controlled and equal laboratory conditions and this is done by the stack manufacturers.
On the other hand, system tests in a controlled environment with extra instrumentation available, in addition to the necessary safety, functionality and output verification, also produce a lot of invaluable information about the quality of integration and data for verifying component and system models to be used system simulations, design of control systems and evaluation of transient behaviour in hardware-in-the-loop control emulations.

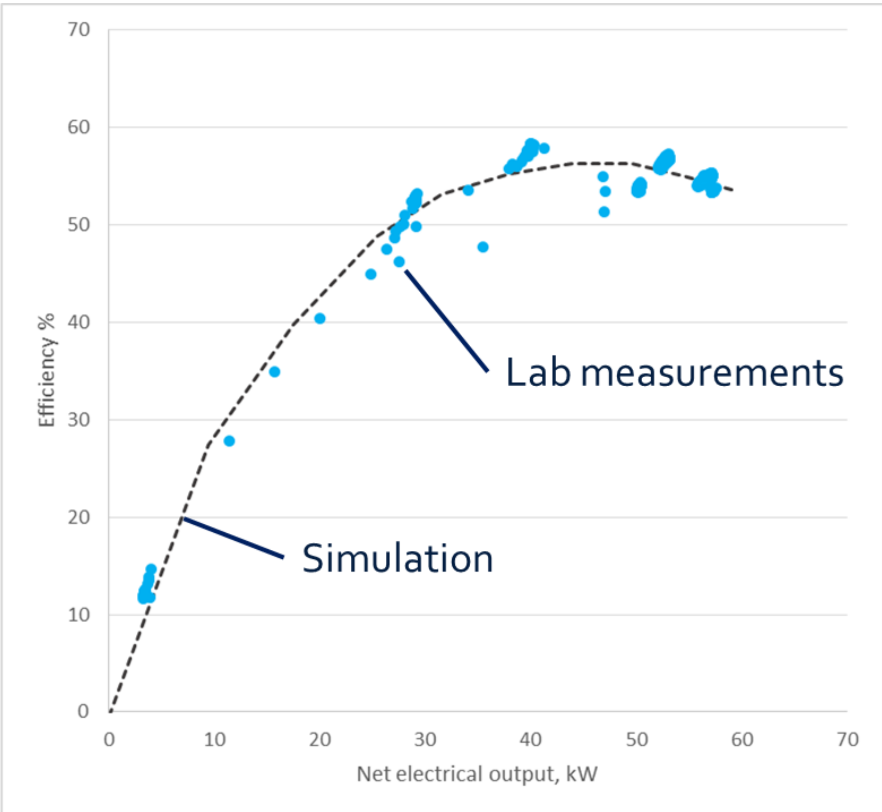

Figure 9 Example of simulated vs. measured net electrical efficiency values at different load points. In laboratory conditions, reasons for deviations can be traced to causes.

9. Shipment

C50 SOFC systems are self-contained, fully equipped power plants. Once factory accepted and tested, work related to the actual SOFC systems' installation is limited as long as site preparations are carried out in due manner. The systems are detachable and can also be moved away from the site, should a need for a more intrusive maintenance activity arise. Also certain internal modules can be replaced with new or refurbished ones, limiting the site work and time needed to fitting. The SOFC modules were transported from Finland to Italy by a truck and lifted in place by a crane. All along, accelerations, inclinations and possible impacts were monitored. The unit started up again in the final installation site and no adverse issues associated to the shipment were detected.

Figure 10. Shipment and installation of the first SOFC1 module.

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 671470. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe research.