

PROJECT FINAL REPORT

Grant Agreement number: FCH JU 278798

Project acronym: SOFCOM

Project title: SOFC CCHP with poly-fuel: operation and management

Funding Scheme: Collaborative project

Period covered: from 01.11.2011 to 30.04.2015

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4.1 Final publishable summary report

Executive summary (not exceeding 1 page).

SOFCOM has been an **applied research project** devoted to demonstrate the technical feasibility, the efficiency and environmental advantages of CHP systems based on SOFC (solid oxide fuel cell technology) fed by different typologies of biogenous primary fuels (biogas and bio-syngas, locally produced) integrated by a process for the CO₂ separation from the exhaust gases and Carbon re-utilization.

The wider objective of SOFCOM is to demonstrate the high interest of electrochemical systems based on high temperature fuel cells to operate as the core of future energy systems with renewable fuels and multi-product configuration, with particular care on CO₂ management through C re-utilization in different processes (electrochemical, chemical, or biological as in SOFCOM).

SOFCOM has developed **two final demonstrations** of complete biogenous fuel-fed SOFC systems:

1. **DEMO 1 Torino (IT)**: field demonstration of WWTU biogas-fed SOFC with CO₂ recovery and reuse; real operating environment. The proof-of-concept SOFC system is able to operate with biogas produced in an industrial waste water treatment unit (WWTU). The plant is in operation as CHP plant, with heat recovery from the exhaust for the production of hot services (hot water). Also, the plant is completed with a CO₂ separation from the anode exhaust and with a section of CO₂ recovery for Carbon reutilization in a photo-bio-reactor for C storage in form of algae (CO₂ sink).
2. **DEMO 2 Helsinki (FI)**: technology validation within in-house test facility of bio-syngas-fed SOFC; in-house validation. The proof-of-concept SOFC system has been demonstrated considering a SOFC stack operating with a syngas from biomass gasification. This demonstration plant is concentrated on the operation of a SOFC stack with a lean gasification fuel, with concerns related to a proper BoP and gas processing for fuelling the fuel cell system.

The Demonstration has been implemented in the context of other 2 axes:

1. **Lab-scale Experimental Analysis Axis**, developed on every section of the whole system at laboratory-scale: fuel production section; fuel cleaning section; fuel processing section; SOFC CHP section; carbon capturing module (oxy-combustion, CO₂ separation, C fixing in algae)
2. **System Analysis Axis** (Energy-Environmental analysis, Scale-Up analysis, repair strategies): 1) modeling of the complete system, devoted to the energy, economic, environmental analysis of the option of SOFC-based CHP plants as distributed systems using local biogenous energy sources; 2) monitoring analysis on the long run, redaction of repair strategies 3) development of guidelines for the scale-up 4) development of pre-normative results 5) LCA analysis

The following targets have been faced:

- Define and operate new proof-of-concept fuel cell systems fully integrated with biomass processing units and carbon sequestration and handling technologies;
- Fuel issues considering poisoning mechanisms, advancing in cleaning and processing technologies;
- Maintenance, safety, repair and de-commissioning of fuel cell systems on a demonstration scale.

Finally, the **Promotional Sentence** is:

Use of renewable fuels (biogas and syngas from biomass gasification) in high efficiency electrochemical generators in CHP configuration with complete CO₂ recovery and Carbon re-use.

A summary description of project context and objectives (not exceeding 4 pages).

In the present and future energy framework, based on the concepts of sustainability, energy security using local resources, maximization of the exergy efficiency of the whole system, a contribution could be based on the following criteria:

- Combined heat and power (CHP) plants, but even better poly-generation plants
- Small to medium sized local plants: distributed generation
- Plants with maximization of the energy recovery from the primary sources: maximum exergy efficiency of the whole system
- Flexibility in the use of local primary sources (biogas, bio-syngas, bio-fuels)
- Easy and efficient CO₂ separation from the plant exhaust, and disposal or reutilization

Few of the state-of-the-art technologies are able to satisfy all these criteria. Some of the new technologies fits better with the requests of the new energy frameworks, and are close to be ready for the market. In this group, energy systems based on Solid Oxide Fuel Cells (SOFC) are gaining more and more interest as they could represent one of the most promising technologies able to address the above criteria.

In fact, among the small to medium size energy technologies, the SOFC offer several advantages over the others:

1. they can reach the highest conversion efficiency: in particular, due to the high electricity fraction, they can obtain the highest exergetic efficiency from the primary fuel.
2. due to high operation temperature, they have better possibilities of operation in CHP configuration.
3. they are static machines with a reduced noise and a safe operation: therefore, they fit particularly well as distributed plants.
4. they are versatile towards primary fuels: pure hydrogen, hydrocarbons, syngas, bio-fuels such as ethanol, biogas and bio-syngas (from biomass and wastes)
5. they are able to emits exhausts in which the CO₂ is highly concentrated, and so easier to be recovered

Nevertheless, especially in the case of biogas and gasification gas fuels, SOFC integrated systems have shown to be not robust enough so far, essentially because of the need of highly reliable fuel cleaning and processing units. Moreover, the components of the system have to be integrated together in a layout mostly operating at medium or high temperatures. A thorough experience in maintenance is therefore necessary in order to develop efficient and cost-effective repair strategies both on the SOFC primary driver as well as for the rest of the Balance of Plant (BoP) of the complete system.

Further general considerations concern the possibility to integrate Solid Oxide Fuel Cells in energy systems with carbon capturing technologies. In fact, the electrochemical reactions taking place in SOFCs can be seen as ‘efficient oxy-combustion reactions’ when referring to the anode side: the exhaust stream at the anode can represent a gaseous mixture with high

CO₂ concentration, easier to separate if compared to the exhausts of conventional internal combustion engines or gas turbines.

In this context, the **general objective of SOFCOM** has been to demonstrate, for the first time in the World, the high interest of electrochemical systems based on high temperature fuel cells to operate as the core of future energy systems centered on the concept of poly-generation: hybrid highly-integrated systems based, as external inputs, on renewable sources and able to generate multiple products (heat&power, fast growing biomass in form of algae, clean water, etc.), with complete heat and mass integration, and complete application of CCU (Carbon Capture and Utilization) procedures. Towards this radical approach, the high temperature fuel cells (HTFCs) can play a fundamental role.

In practical terms, SOFCOM has been an **applied research project** devoted to demonstrate the technical feasibility, the efficiency and environmental advantages of CHP based on SOFC (solid oxide fuel cell technology) fed by different typologies of biogenous primary fuels (biogas and bio-syngas, locally produced) integrated by a process for the CO₂ separation from the exhaust gases.

SOFCOM has developed **two final demonstration** of complete biogenous fuel-fed SOFC systems:

- 1) **DEMO 1 Torino (IT)**: field demonstration of WWTU biogas-fed SOFC with CO₂ recovery and reuse; real operating environment. The first proof-of-concept SOFC system is able to operate with biogas produced in an industrial waste water treatment unit (WWTU). The plant will be in operation as CCHP plant, with heat recovery from the exhaust for the production of hot services (e.g. hot water) and conditioning services (through an adsorption chiller). Also, the plant will be completed with a CO₂ separation from the anode exhaust and with a section of CO₂ management (and disposal) integrated with the primary fuel processing system.
- 2) **DEMO 2 Helsinki (FI)**: technology validation within in-house test facility of bio-syngas-fed SOFC; in-house validation. The second proof-of-concept SOFC system will be demonstrated considering a SOFC stack operating with a syngas from biomass gasification. This second demonstration plant will be concentrated on the operation of a SOFC stack with a lean gasification fuel; all the concerns are related to a proper fuel gas cleaning for fuelling the fuel cell system.

The Demonstration has been implemented in the context of other 2 research axes:

- 1) **Lab-scale Experimental Analysis Axis**, developed on every section of the whole system at laboratory-scale: fuel section; cleaning section; fuel processing section; SOFC CCHP section, for the production of electrical and thermal (cooling and heating) power; carbon capturing module.
- 2) **Macro-scale Analysis Axis** (Energy-Environmental analysis, Industrial Scale-Up analysis, repair strategies): preparatory to the Demonstration Axis: modelling of the complete system, devoted to the energy, economic, environmental analysis of the option SOFC-based CHP plants as distributed systems using local energy sources; validation of the plants, with the subsequent development of guidelines for the scale-up and industrialisation of such plants, and the definition and redaction of repair strategies, the monitoring analysis on the long run, and the development of pre-normative results leading to recommended practices for those plants.

In particular, the following target have been faced:

- (1) Fuel issues considering detailed poisoning mechanisms, advancing in cleaning and processing technologies;
- (2) Define and operate new proof-of-concept fuel cell systems fully integrated with biomass processing units and carbon sequestration and handling technologies;
- (3) Maintenance, safety, repair and de-commissioning of fuel cell systems on a demonstration scale

In this context, several issues are addressed:

- the impact of the fuel contaminants on the SOFC and fuel processing units, and consequently the research and analysis of gas cleaning;
- the operation of the integrated plants in -CHP configuration;
- the design and optimization of the carbon sequestration-management modules;
- the analysis and implementation of maintenance and repair strategies of those plants.

Finally, the lessons learned from the demonstration are used for pre-normative issues and scale-up analysis of this typology of integrated plants.

From a **wider perspective**, the developed proof-of-concept has been devoted to demonstrate the high interest of electrochemical systems based on high temperature fuel cells to operate as the core of future energy systems with renewable fuels and multi-product configuration, with particular care on CO₂ management through C re-utilization in different processes (electrochemical, chemical, or biological as in SOFCOM).

The proof-of-concept SOFC system, installed in Torino (IT), operates with biogas produced in an industrial waste water treatment unit (WWTU) in CHP configuration, and with the CO₂ separation from the anode exhaust sent to a section of CO₂ recovery for Carbon reutilization in a photo-bio-reactor for C storage in form of algae (CO₂ sink). Therefore, the proof-of-concept demonstrates a poly-generation system based on the use of renewable fuels (biogas) in high efficiency electrochemical CHP generators, with complete CO₂ recovery and Carbon re-use.

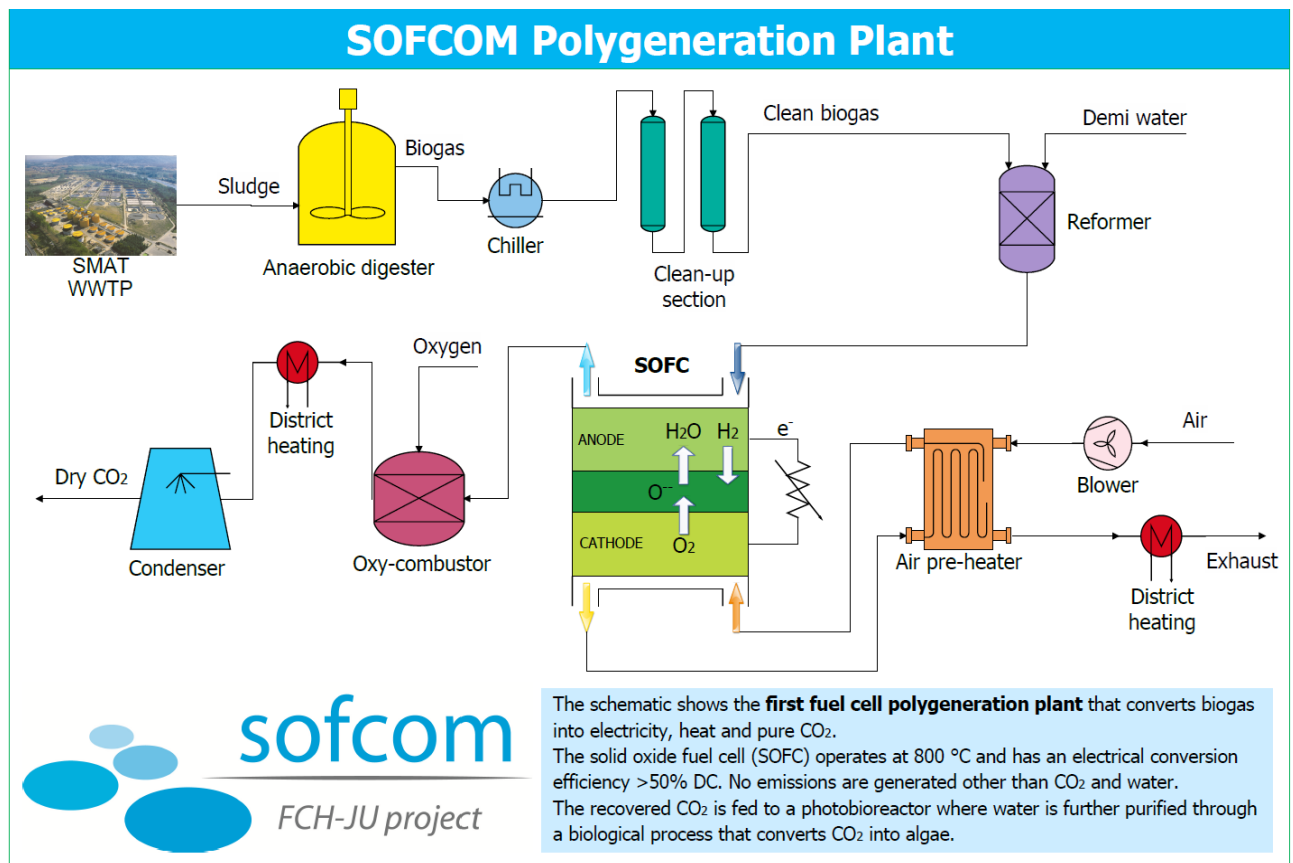


Figure 1. Schematic diagram of the proof-of-concept in Torino (first part: biogas cleaning and processing, SOFC, oxy-combustor of anode exhausts, and H₂O condensation for CO₂ recovery)



Figure 2. Picture of the proof-of-concept in Torino



Figure 3. SOFC stack module installed and insulated in the in-house proof-of-concept in Helsinki.

Description of the main S&T results/foregrounds (not exceeding 25 pages),

Summary of the main results achieved

Table 1. Project objectives and achievements

No.	Programme Objective/ Quantitative target	Corresponding project objectives/ targets	Achievements
	MAIP objectives		
1	High electrical efficiencies of 45%+ for power systems and of 80%+ for CHP systems, with lower emissions and use of non-fossil fuels.	From the first analysis, the figures are as follows: a) 53.00% of the primary fuel is converted in high value electric power; b) 45.78% of the primary fuel is converted in low grade heat flow, but fully useful in the WWTU plant to supply the heat requirements of the thermo-phillic sewage digesters; c) 1.22% of the primary fuel is converted back in useful biomass, which can be re-inserted in the digester for biogas production, or used for other applications (e.g. bio-fuel productions). Also, it has to be considered that: a) the biogas is a completely sustainable fuel, b) the system provides a complete closed loop of the Carbon atoms	The DEMO has been tested from December 2014 to May 2015 with complete success.
2	Demonstration activities target proof-of-concept, technology validation or field demonstrations	SOFCON develops two final demonstration of complete biofuel-fed SOFC systems: DEMO 1 Torino (IT): field demonstration of WWTU biogas-fed SOFC with CO ₂ recovery and reuse; real operating environment. DEMO 2 Helsinki (FI): technology validation within in-house test facility of bio-syngas-fed SOFC; in-house validation.	DEMO 1 Torino (IT): done. DEMO 2 Helsinki (FI): done.
3	Field demonstration activities are split into small (residential and commercial applications) and large (distributed generation or other industrial or commercial applications) scale.	The DEMO 1 in Torino is a small scale demonstration activity but performed in a real industrial application scale. The DEMO 2 in Helsinki is a small scale demonstration activity but with emphasis on future scale-up (biomass gasification fuel).	DEMO 1 Torino (IT): done. DEMO 2 Helsinki (FI): done.
	AIP objectives		
4	Development of proof of concept prototypes that combine fuel cell units into	SOFCON develops of two proof-of-concept demonstration plants, which integrates SOFCs into	DEMO 1 Torino (IT): done. DEMO 2 Helsinki (FI): done.

	complete systems, performing integration and testing with fuel delivery and processing subsystems; interface with devices featuring delivery of customer requirements (e.g. power, heat, cooling and CO ₂ capture), also integrating renewable sources and other services wherever appropriate	complete systems. The demonstration site in Torino (Italy) consists in SOFC generator fully integrated in a large waste-water treatment plant producing biogas; the generator works in a cogenerative mode, producing electrical power, plus heat; it is also integrated with a CO ₂ separation and reutilization module (photo-bio-reactor for algae water and Carbon fixing). The demonstration site in Helsinki (Finland) is based on the integration of the SOFC with another fuel typology: a bio-syngas (from gasification) is used to feed the SOFC unit, which works in CCHP configuration.	
5	Identification of technical and economic requirements in order to be competitive in the marketplace	Complete analysis from the energy and economic point of view, following the real experience performed in the Demonstration Activity, with a scale-up analysis of the integrated SOFC systems studied.	Exploitation plan of biogas-fed SOFC systems completely performed (Deliverable D8.5).
6	Validation activities, performed in a real system environment or with real equipment in a simulated system environment	The proof-of-concept validation of the tested systems on the demonstration sites is one of the main results of the project; this is followed by a close examination of the lessons learned, which will eventually enable us to identify the reliability of the SOFC integrated systems, weaknesses, and eventually to establish the market maturity.	DEMO 1 Torino (IT): done. DEMO 2 Helsinki (FI): done.

Table 2. Assessment against international technological state of the art

No.	International state of the art (SoA)	International level SoA	Project achievements
1	Analysis of biogas contaminant effects on SOFC anodes: halogens, siloxanes, combined effects	Few analysis of halogens and siloxanes effects, no analysis of combined effects	Complete analysis of halogens (HCl, C ₂ CL ₄), siloxanes (D ₄ , L ₄) and combined effects
2	Experimental analysis of CO ₂ recovery from anode exhaust using micro-algae	No examples so far	Evaluation of complete CO ₂ recovery
3	DEMO of complete biogas-cleaning-SOFC-CO ₂ recovery from anode exhaust	No examples so far. Only one example of H ₂ recovery from anode exhaust in the Orange County Sanitation District (Fountain Valley, USA).	Complete DEMO of the proof-of-concept
4	DEMO of SOFC stack fed	No real plant existing, tests done at	Complete test of real

	with lean fuel (syngas from biomass gasification)	the lab level.	equipment in a simulated system environment
5	Scale-up and exploitation analysis	No large real plants based on SOFC already installed.	Complete scale-up analysis for next installation in EU of a biogas-fed SOFC based plant (size around 175 kW).

Lab-scale Experimental Analysis Axis

Lab-scale: influence of pollutants on SOFC anodes and fuel processing reactions, and gas cleaning

Impact of pollutants on single cells

The activity is described in detail in the Deliverables D2.1 “Effect of Pollutants on single SOFCs. Guidelines for implementation of proofs-of-concepts” and D2.2 “Effect of Pollutants on single SOFCs. Advances in poisoning mechanisms”.

The goal has been to accomplish experimental campaigns on SOFC single cells provided by TOFC AS concerning the effect of biogas contaminants on the cell performance and stability. The main purposes of these experiments have been:

- To evaluate the threshold tolerance towards different contaminants
- To investigate degradation mechanisms

The impact of selected biogas and gasified biomass contaminants in the anode feed of the SOFC on the performance and chemical/electro-chemical stability of TOFC single cells has been evaluated.

Degradation and de-activation mechanisms in Ni-YSZ anodes have been reviewed and analysed with respect to the experimental results obtained. The selected contaminants were H₂S, C₄H₄S and COS as sulfur compounds, both inorganic and organic halogen compounds, that were HCl and C₂Cl₄, respectively, ethylene, C₂H₄ and C₇H₈ and C₁₀H₈, that is a well-known carbon precursor on Ni catalyst due to the double C-bond, and finally D4 as siloxane model compound.

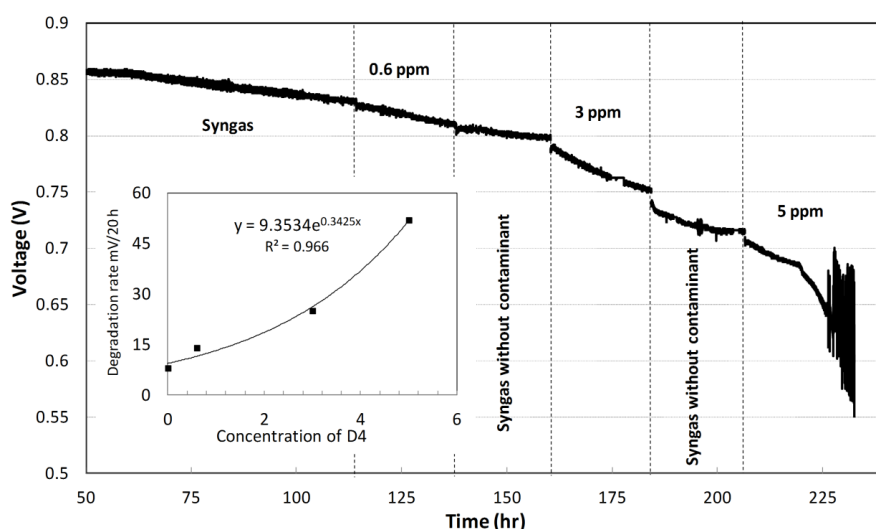


Figure 4. Time-dependent decay of cell voltage at constant current density (0.25 A/cm²) at 750°C, with biogas reformate and various D4 impurity levels.

Impact of pollutants on short-stacks

The activity is described in detail on Deliverables D2.3 “Effect of Pollutants on SOFC Short Stacks. Guidelines for implementation of proofs-of-concepts” and D2.4 “Effect of Pollutants on SOFC Short Stacks. Advances in poisoning mechanisms”.

The effect of single contaminants in the anode feed of the SOFC on the performance and chemical/electro-chemical stability of TOFC short stacks has been evaluated. Degradation and de-activation mechanisms in Ni-YSZ anodes have been reviewed and analysed with respect to the experimental results obtained. The tested compounds have been siloxanes (model compound D4), HCl, halocarbons (model compound C2Cl4) and C2H4 (model compound with C2-bond that is a well-known precursor of carbon-deposition). The effect of H2S and COS has been also investigated. Finally the impact of partial direct internal reforming of biogas in the SOFC anode has been assessed through a dedicated experiment.

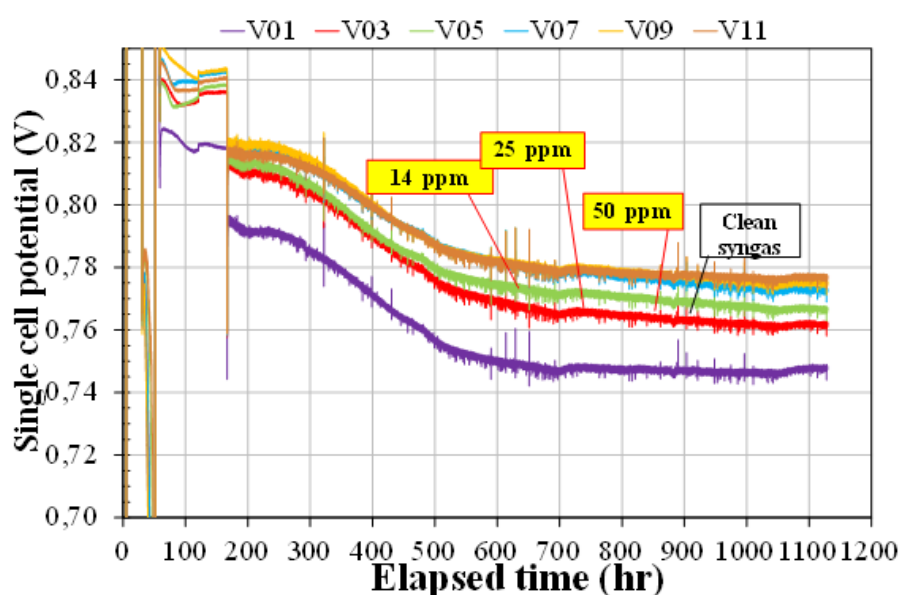


Figure 5. Durability test of stack with up to 50 ppm(v) of HCl with biogas reformat fuel.

Impact of pollutants on biogas fuel processing

The activity is described in detail on Deliverable D2.5 “Effect of Pollutants on Fuel Processing. Guidelines for implementation of proofs-of-concepts” and D2.6 “Effect of Pollutants on Fuel Processing. Advances in poisoning mechanisms”.

The impact of pollutants on biogas fuel processing has been carried out; in detail, first were selected both catalyst and operative conditions for the fuel processor section developed for the SOFC proof-of-concept located in Turin, Italy (SOFCOM-Deliverable 2.5); successively a depth analysis on catalytic performances using biogas stream with poisoning compounds were investigated in order to reach significant advances in the analysis of the fundamental process mechanisms.

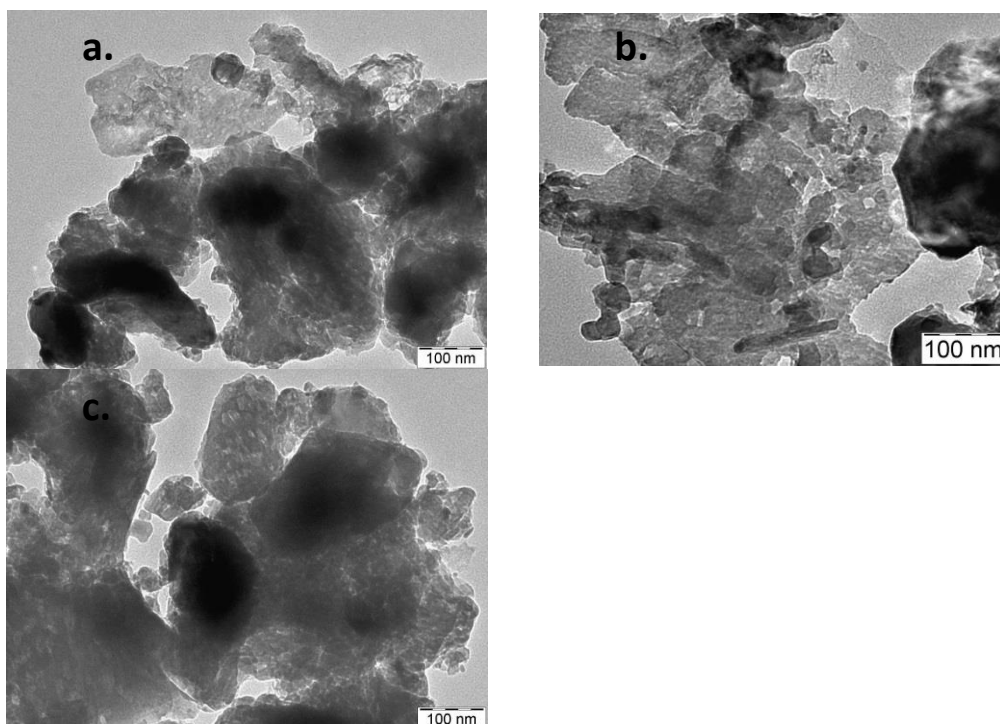


Figure 6. TEM images on fresh and spent catalysts: (a) Ni catalyst “fresh”; (b) Ni catalyst “used” $\text{CH}_4/\text{CO}_2=55/45\text{mol}\%+\text{H}_2\text{S}+\text{HydroC.}$; $\text{H}_2\text{O}/\text{CH}_4=2\text{ mol}\%$; $\text{GHSV}=15,000\text{ h}^{-1}$; $\text{T}=1073\text{K}$; $\text{P}=1\text{bar}$ (c) Ni catalyst “used” $\text{CH}_4/\text{CO}_2=55/45\text{mol}\%+\text{HydroC.}+\text{D5}$; $\text{H}_2\text{O}/\text{CH}_4=2\text{ mol}\%$; $\text{GHSV}=15,000\text{ h}^{-1}$; $\text{T}=1073\text{K}$; $\text{P}=1\text{bar}$

Fuel cleaning

The activity is described in detail on Deliverable D2.7 “Fuel Cleaning. Guidelines for implementation of proofs-of-concepts” and D2.8 “Fuel Cleaning. Advances in poisoning mechanisms”, available on M38.

The biogas cleaning has been studied for better understanding of the biogas cleaning and knowledge acquisition of the latest scientific advances in this topic. Different processes were studied for the removal of the main impurities in biogas (hydrogen sulphide and siloxanes) for single, combined and integrated processes. Patents and commercial solutions for biogas cleaning were also studied.

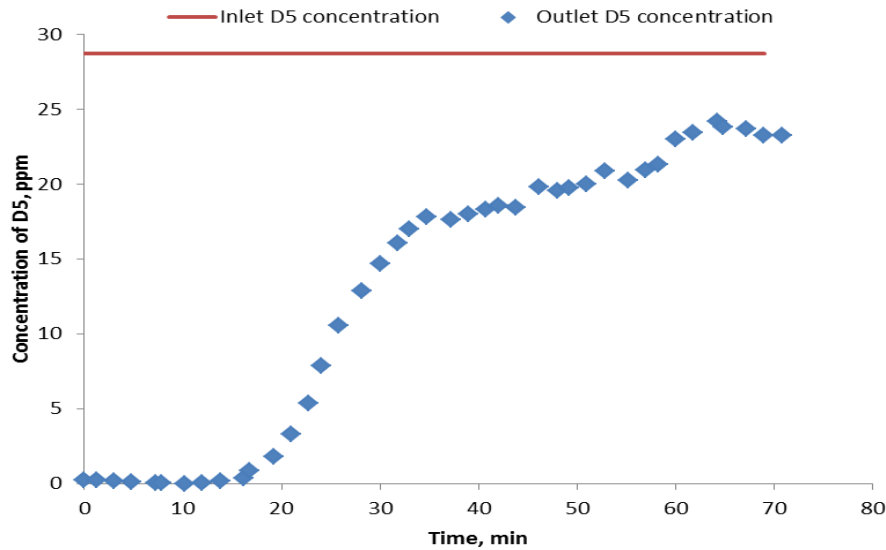


Figure 7. Breakthrough curve of D5 for activated carbon at 200°C.

Lab-scale activities: carbon sequestration technologies (WWTU biogas)

Oxygen separation membranes and Oxycombustion of anodic spent fuel

The activity is described in detail on Deliverable D3.1 “Performance tests of the oxycombustor unit”.

Several potential concepts of oxy-combustor have been analysed and discussed. Three combustors have been build and two of the units were prepared for extensive testing under operating conditions corresponding to the operational parameters of a full scale demonstration plant. Flue gases exiting the oxy-combustor which was developed in frame of SOFCOM project (Task 3.1) has been directed to algal-based carbon capture and sequestration module. Operational characteristics of the oxy-combustors, which were designed and build to allow efficient operation in wide range of parameters, were defined by the characteristics of SOFC stack used in the project.

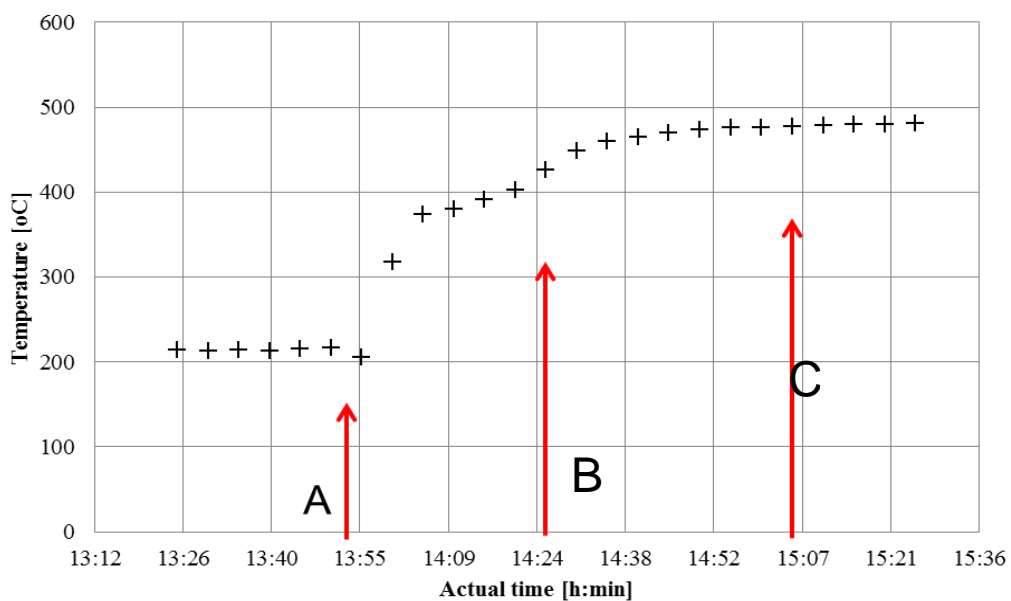


Figure 8. Experimental investigation of flue gases temperature during start-up of oxy-combustor III. Total flow and composition of the combustible gas, corresponds to nominal operating conditions of the DEMO (case I). A – beginning of combustion, hydrogen and oxygen are supplied to the burner (13:54), B – carbon monoxide is supplied to the burner (14:25), C – stabilization of combustion temperature (15:05).

CO2 management: internal process optimization, CO2 sequestration technologies and Condensation, Lab scale test

The activity is described in detail on Deliverable D3.2 “Start up and testing of the condenser system”.

For water removal from a CO₂/H₂O-containing flue gas of a high temperature fuel cell a two-part device, consisting of a cooler-condenser and a membrane-based system for residual humidity removal, has been developed, constructed and tested. For calculating the cooler-condenser with its water cooled, cross-flow tube bundle, a thermodynamic calculation model was developed that is taking into account the particularities of partial condensation of an inert gas-steam-mixture. In order to reduce the formation of mist in the cooler condenser, a concept with internal recirculation of condensate was realized. In the device for residual humidity removal a modified drying membrane, originally designed for drying compressed air, was used in conjunction with an oil-free piston compressor. To control the flow rate, the system works with a closed loop circuit, which allows a largely autonomous operation for integrating the system in a demonstration plant for CO₂ separation. With a specially designed test rig the design calculations could be verified, practical operation of the system could be demonstrated. The gas-steam-mixture, provided by the test rig at similar conditions to the fuel cell exhaust gas, could be dried to a water content of less than 500 [ppm] within a wide range of operation parameters.

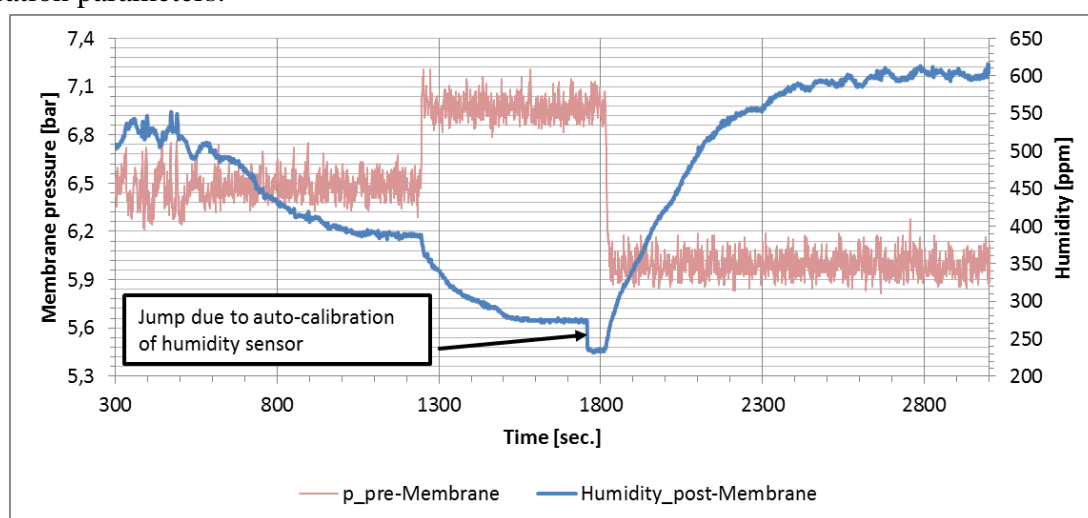


Figure 9. Variation of the humidity due to variation of the membrane pressure.

Selection of materials for CO₂-lines

The activity is described in detail on Deliverable D3.3 “Utilization of CO₂ for carbon biofixation and wastewater treatment: removal of nutrients by algae growing”.

The bio-fixation of CO₂ and its application on the waste water treatment were evaluated and developed for the management of the CO₂ captured from a flue gas of a Solid Oxide Fuel Cell as part of the work developed in the SOFCOM EU project. Microalgae from a natural pond

fed with secondary treated waste water were selected for their ability to compete against natural selection and avoid the risk of intrusion of new species in the environment. Two lab setups were developed to grow microalgae crops for its use as inoculation in the demonstration trials to be carried out in Torino. From these, the best operating conditions for the growth of the microalgae at lab were identified. Both, carbon bio-fixation and nutrients removal capacities were demonstrated and characterized. In addition, the best configuration for a photobioreactor was evaluated using CFD to simulate the distribution and dissolution of the CO₂ along the tubes of the photobioreactor and its influence on the algae growth.

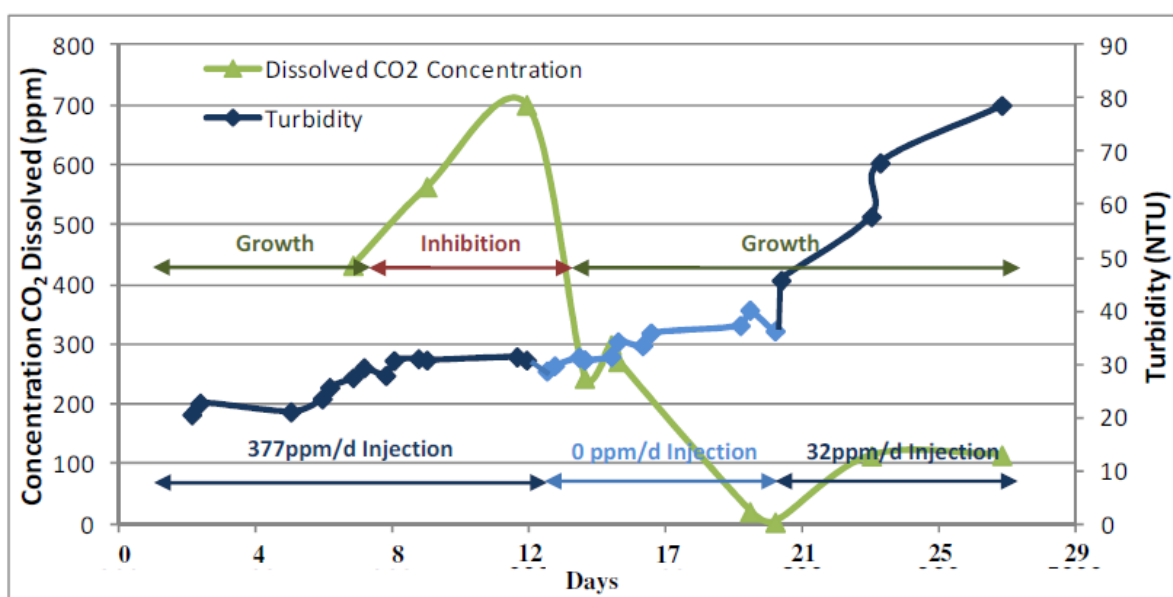


Figure 10. Growth of microalgae versus concentration of CO₂ dissolved in water.

Macro-scale Analysis Axis

Conceptual and Techno-economic study of combined waste water plant and SOFC system (50 kW – 1 MW)

Analysis of existing biogas production plant

The activity is described in detail on Deliverable D4.1 “Analysis of the operation of the SMAT (Torino) sewage plant and record of historical data”.

This activity has been devoted to the study and the description both of the existing biogas production plant in Castiglione and of the state-of-the-art concerning the microbiological and biochemical aspects of the anaerobic digestion of waste water sludge focusing on control of the sulphur and other SOFC pollutant compounds into the produced biogas.

The SMAT centralized urban (civil and industrial) waste water treatment plant is located in Castiglione Torinese in the province of Torino (Italy). Built in 1984, it is the greatest waste water treatment plant in Italy and it serves over 2 million population equivalents in the metropolitan area of Turin treating over 620.000 cubic meters per day of waste water. The whole treating plant is divided in two main parts:

- Water treatment line: 4 parallel modules where water is purified by a chemical-physical-biological process;

- Sludge treatment line: where sludge produced by water treatment is thickened, biologically stabilized (partially converting its organic content in biogas and then in electrical and thermic power) and then dewatered before disposal.



Figure 11. Picture of the SMAT centralized urban (civil and industrial) waste water treatment plant

Methane content has always been around 60%, with values varying historically between 57.3% and 64.8%, a range acceptable for feeding SOFC. H₂S content is normally measured, except some peak values, well below 100 ppm threshold. This level of hydrogen sulfide content, which is quite low compared to other waste water biogas, is obtained thanks to the precipitation effect due to the presence in sludge of iron salts used for phosphorus removal. This level of H₂S, although not detrimental for internal combustion engines and not producing significant corrosion phenomena, is not acceptable in SOFC feed. For that reason, it has been of fundamental importance the study of a proper and effective cleaning system of biogas fed to the fuel cells, to reach hydrogen sulphide level below 1 ppm.

In the SOFCOM activity, the monitoring of the microbial community and especially the MB community and SRB and SOB communities in the anaerobic digester has also been done, in order to promote correct operational control. This activity was strictly connected to the one performed in WP2 by UNITO, which has produced as a result the added Deliverable D2.9 “Analysis of micro-biological methods to decrease the total sulphur and to increase the total methane in the biogas exiting the digester”.

Technical analysis of an integrated system WWTU biogas + SOFC

The activity is described in detail on Deliverable D4.2 “Conceptual and technical layout for the biogas integration with the SOFC generator”.

Starting from the site description, the technical data of each unit of the plant has been analysed. Also, critical issues like pressure and working conditions have been discussed, and auxiliary services and components have been listed and explained.

In the design phase, the plant has been subdivided into specific units, as can be seen from Figure 12, for better analyzing the main characteristics and critical issues of each section.

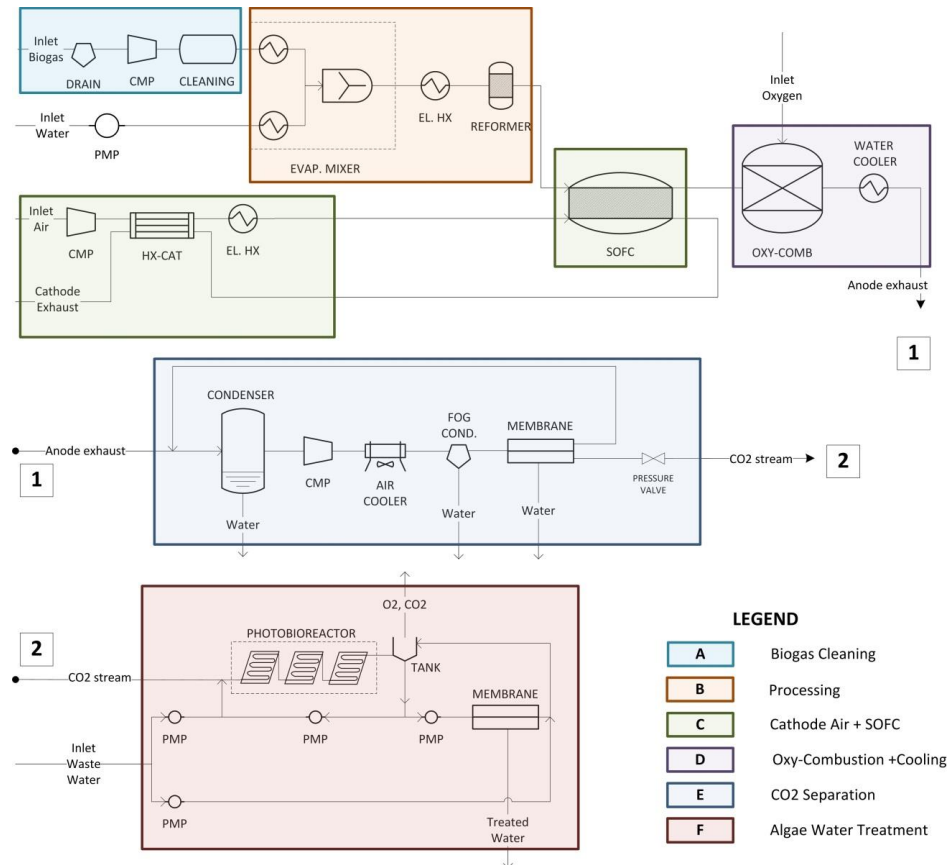


Figure 12. Specific sections of the an integrated system WWTU biogas + SOFC

In the SMAT plant, the municipal waste-water is treated producing a sludge that is eventually digested in thermophilic biogas reactors. Normally, the as-produced biogas is burnt in Internal Combustion Engines that provide a fraction of the overall electricity consumed on-site by the WWTP. In the framework of the SOFCOM project, a relatively tiny portion of the produced biogas has been used to feed the SOFC demonstration plant. A biogas blower has been required to feed the fuel mixture (found slightly above the atmospheric pressure in the reservoir tanks) across the various plant sections. An inlet pressure of 1.1-1.2 bars was sufficient. After the blower, the biogas has been cleaned in order to remove harmful contaminants for the SOFC. According to historical data collected in the period from Jan. 2012 to Sept. 2012 (SMAT), cyclic siloxanes (D4 and D5), halogens and sulfur compounds have to be removed carefully to avoid poisoning of the reformer unit and the SOFC. The clean biogas has been converted via an external steam reformer to a bio-syngas rich in H₂ and CO that was feeding to the SOFC stack. The anode-off gas was burnt with pure oxygen to yield an almost pure CO₂-H₂O stream. The latter was condensed in a dedicated unit to produce a relatively pure CO₂ stream complying also with purity requirements for sequestration. Finally, the pure CO₂ stream was eventually used (re-cycled) for carbon bio-fixation in microalgae reactors with additional waste-water treatment via biological nutrients removal. Critical issues as the pressure drop analysis along the biogas line, the off-design conditions of the plant, the analysis of the necessary BoP components and their services requirements, are fully described in the Deliverable D4.2.

Energy, environmental and economic analysis of an integrated system WWTU biogas + SOFC

The activity is described in detail on Deliverable D4.3 “Optimal plant configurations for the ‘biogas+SOFC’ integration”.

Biogenous fuels have a wide potential in terms of availability and diffusion. The fuels considered are not only of interest because of their carbon neutrality, but also for their high market potential.

For both SOFC-based systems (a) SOFC system operating with biogas, (b) SOFC system operating with bio-syngas from biomass gasification, the activities have been: (1) AspenPlus® model for each plant size; (2) Energy analysis; (3) Sensitivity analysis and subcases analysis; (4) Building of a common economic database with cost functions for each plant component; (5) Economic analysis.

A detailed system analysis of biogas fed SOFC plants has been performed. Different sizes, configurations and layouts have been analysed from a technical and economic point of view. The first presented step was the case studies and the methodology definition. After, a detailed model description was performed. Finally, results have been presented with analysis of different configurations and optimization achieved.

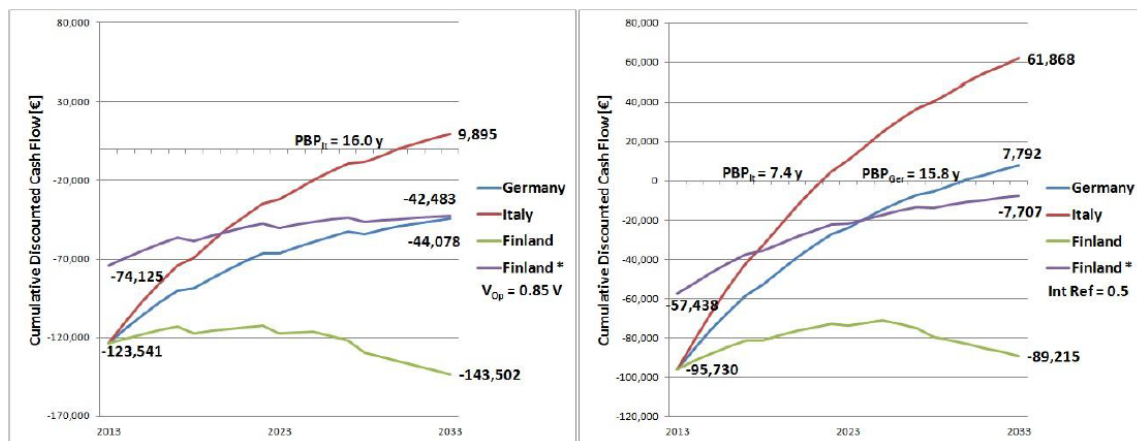


Figure 13. NPV and PBT for $V_{Op} = 0.85 V$ and 50 % internal reforming under SR.

Potential impact deriving from the adoption of integrated system WWTU biogas + SOFC across EU

The activity is described in detail on Deliverable D4.4 “Technical report on the potential impact of biogas exploitation with the SOFC technology in waste-water treatment plants”.

The biogas potential in the EU region has been analysed, with focus on Italy, Germany, France and North Europe (Sweden, Denmark and Finland). The resources for biogas production include agricultural crops directly provided for energy, livestock residues, municipal solid waste and wastewater. The analysing methodology has been obtained from several scientific articles and papers.

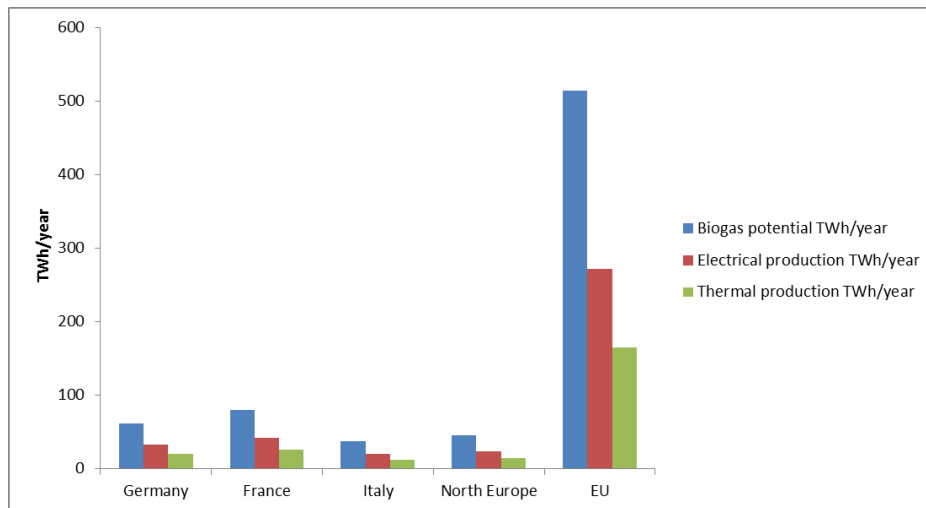


Figure 14. Biogas potential: from primary energy to electrical and thermal generation with SOFC.

LCA of integrated system WWTU biogas + SOFC

The activity is described in detail on Deliverable D4.5 “LCA of biogas exploitation with the SOFC technology in waste-water treatment plants”.

The Life Cycle Assessment (LCA) of biogas-fed Solid Oxide Fuel Cell (SOFC) integrated with a CO₂ recovery system has been carried out. The goal of this work was to evaluate the environmental performance of a SOFC fed with wastewater biogas and to compare it with traditional technologies (internal combustion engines and micro turbines). CO₂ recovery is achieved through a tubular photobioreactor, fixing carbon in form of algae. Uncertainty analysis of Life Cycle Impact Assessment (LCIA) results is also included in the study. The results show that environmental performance of SOFC manufacturing highly depends on the quantity of steel and electricity employed. During operation, instead, the highest burdens are associated to the fuel chain. Concerning this, two scenarios for biogas operation have been depicted, underlining the benefits of introducing a sludge thickening machine in digester operation. The chosen design for the photobioreactor proved to be unsustainable, consuming more energy than what it produces and being responsible for more carbon emissions than what fixed in algae. In the end, SOFC offers the lowest environmental burdens in respect to its competitors. Moreover, the studied energy path proved to be an interesting choice for a clean energy production.

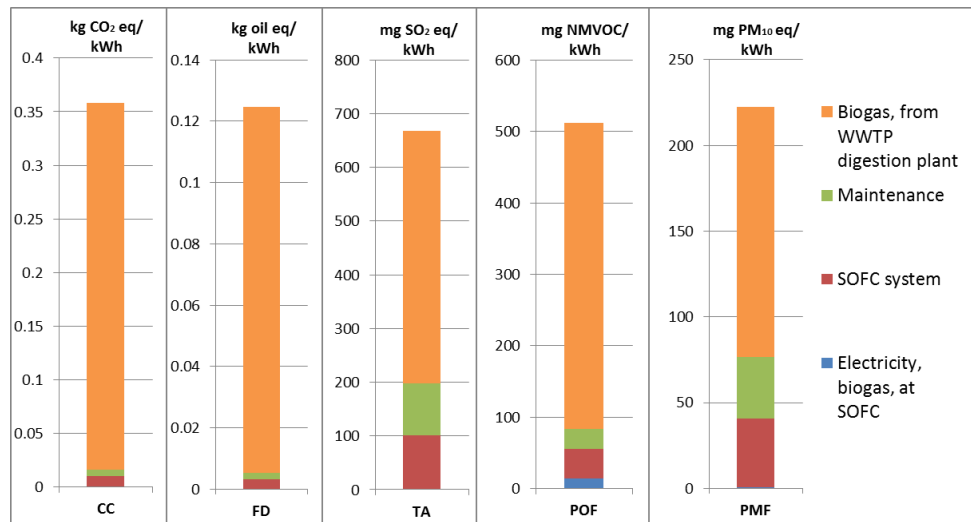


Figure 15. LCIA results for electricity generation, at biogas fueled SOFC. The biogas used refers to the first scenario of digester operation, without sludge thickening. Each bar represents one of the impact categories

Conceptual and Techno-economic study of combined gasification plant and SOFC system (50 kW – 1 MW)

Potential impact deriving from the adoption of Gasification plant and SOFC systems across EU

The activity is described in detail on Deliverable D5.1 “Optimal process concepts for gasification based SOFC processes”.

This first activity has been devoted to the analysis of several potential concepts for combining gasification to SOFC.

The aim of this work was limited to concepts which would be realistic in the near future. Thus the activity has focused on small scale gasification –SOFC concepts and excluded oxygen blown gasification technology which is not feasible in as small scale as this due to the high investment and operating costs of the oxygen production plant. The gasification technologies considered in this study are indirectly heated steam gasification and air blown gasification.

These concepts included two indirectly heated steam gasification technologies, Biomass-Heat Pipe Reformer and fast internally circulating fluidised bed gasifier (FICFB), and two air blown gasification technologies, downdraft gasifier and Viking gasifier. The first technical analyses and process simulations have been carried out and the results are reported in this deliverable. The calculated net electrical efficiency of the whole power plant concepts varied from 27% from simpler design to 65% from more complicated application combining SOFC and GT.

The economic feasibility is affected by gasification technology and gas cleaning process but also by the price of the electricity and by the price and availability of suitable biomass in the European Union. Besides SOFC has to compete with gas engines and other applications, which are suitable for producing electricity from gasification gas.

Biomass-Heat Pipe Reformer (BioHPR)

Based on the allothermal concept, the Biomass Heatpipe Reformer has two zones, the combustion zone and the gasification zone (or reformer). In the gasification zone biomass is

heated up and gasified under the presence of steam as gasification medium, so that mainly H_2O , H_2 , CO , CH_4 , CO_2 and charcoal are produced. Residual charcoal is transported from the gasifier to the combustion chamber where it is burnt to provide the energy necessary for the gasification.

Generated heat is transported from the combustion- to the gasification zone via heatpipes, which are containing alkali metals as working fluid, thus providing the necessary amount of energy.

To date, utilizing the Biomass-Heat Pipe Reformer (BioHPR) the practicability of allothermal gasification with heatpipes has been demonstrated in several 72h tests.

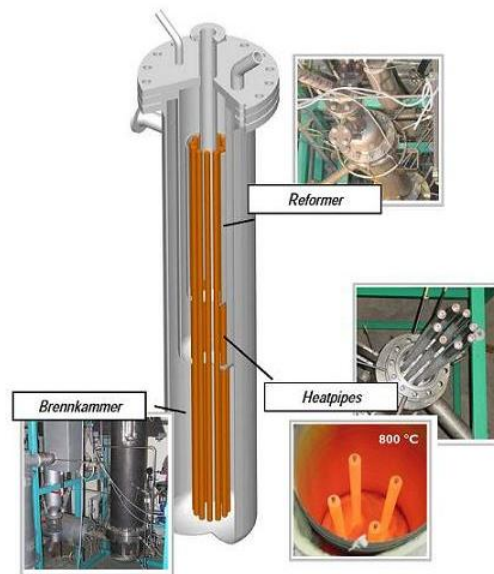


Figure 16. Basic concept of the BioHPR gasification system

Downdraft gasifier

Downdraft gasification technology is suitable for small scale (below 2 MW thermal input, based on LHV). The technology is based on autothermal heating and air is used as oxidising media. A schematic figure of the reactor is presented in the Figure 17. In downdraft gasifier biomass is fed at the top into the reactor. Air is introduced to the gasifier at the throat of the gasification reactor to insure effective mixing of the gases in the hot oxidising region. The temperature may reach $1000^{\circ}C$ in the high temperature region leading to very low tar content in the product gas. At the bottom of the reactor there is a reduction zone. When raw gas is conducted out from the reactor it may flow through the reactor jacket to heat the incoming feedstock. The gas temperature at the outlet of the reactor is below $800^{\circ}C$.

Typical features of a well working downdraft gasifier are very good quality of raw gas and low tar content. The standard type of downdraft gasifier is suitable for only small scale operation due to its basic design.

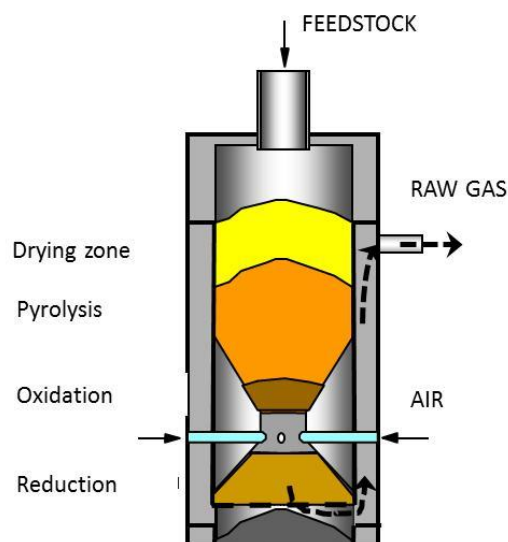


Figure 17. Schematic diagram of a typical downdraft gasifier.

Viking gasifier

The Viking gasifier is a directly heated, fixed bed gasifier based on a relatively novel two-stage concept using air as a gasifying agent. The gasification process performs a thermally staged gasification with intermediate partial oxidation for tar cracking. As described in Figure 18, the feedstock, i.e. wood, is first heated to 500–600°C and partially decomposed in a screw pyrolysis unit. By partial oxidation of the gas phase at around 1300°C, tars are thermally cracked. The remaining solid species are gasified in a fixed bed. The synthesis gas leaving the gasifier at 700–800°C has to be cleaned to remove particles and condensates.

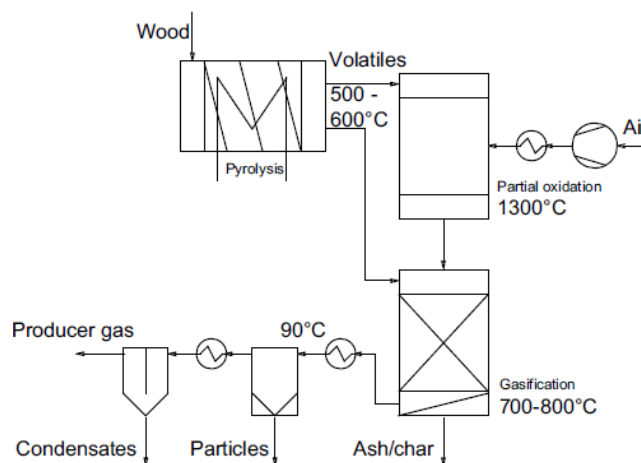


Figure 18. Schematic flowsheet of the Viking gasifier (Gassner 2009).

Both producer gas from indirectly heated gasification and air blown gasification technologies has its advantages and drawbacks. The gas from indirectly heated gasification has higher heating value due to the absence of diluting nitrogen, however, the moisture content is quite high for SOFC. The producer gas from air blown gasification is very dilute for SOFC. However, these gasification technologies may not be competitors as they may be feasible in the different scale. Both air blown gasification technologies, downdraft gasification and Viking gasification, are suitable in small scale, whereas indirectly heated gasification is typically more feasible in higher scale.

Gasification plant and SOFC system

The activity is described in detail on Deliverables D5.2 “Techno-economic evaluation report on gasification based SOFC processes: Italian and Finnish case studies” and D5.3 “Technical report on the potential impact of biomass exploitation with the SOFC technology in gasification plants”.

The thermo-economic potential of several different system configurations combining wood biomass gasification and Solid Oxide Fuel Cell (SOFC) has been evaluated. The systems have been considered at small and medium scale, 100 kW and 8 MW of thermal power input respectively. Concerning gasification the nowadays most elaborate technologies have been chosen, which comprise the fairly wide-spread small scale downdraft gasification technology, the FICFB gasifier in Güssing, often titled the state-of-the-art for biomass gasification at small and medium scale, the widely known Viking gasification technology, an oxygen blown circulating fluidized bed gasifier, and the innovative Heat-Pipe-Reformer. A common SOFC model was linked to the different gasification technologies and for some configurations, CO₂ capture was also considered. It has been found that coupling these different gasifiers to SOFC does lead to very different overall system characteristics, thermodynamically, as well as economically. The competitiveness of different process options has been systematically compared by applying a coherent approach combining flowsheeting, energy integration and economic evaluation. The analysis revealed that, besides the gasification technology and system size, the achievable process integration is a key point. In fact, maximising the internal heat recovery and valorising the waste heat, plays an important role for efficiency and cost. In the economic analysis subsidies scheme of four different European countries, related to the efficient energy conversion of biomass, have been considered. Besides the different values in terms of “feed-in remuneration tariff”, the analysis leads to assess that the investment profitability for the biomass gasification SOFC systems strictly depends on the SOFC cost. A sensitivity analysis on the impact of this factor on the system costs was finally performed.

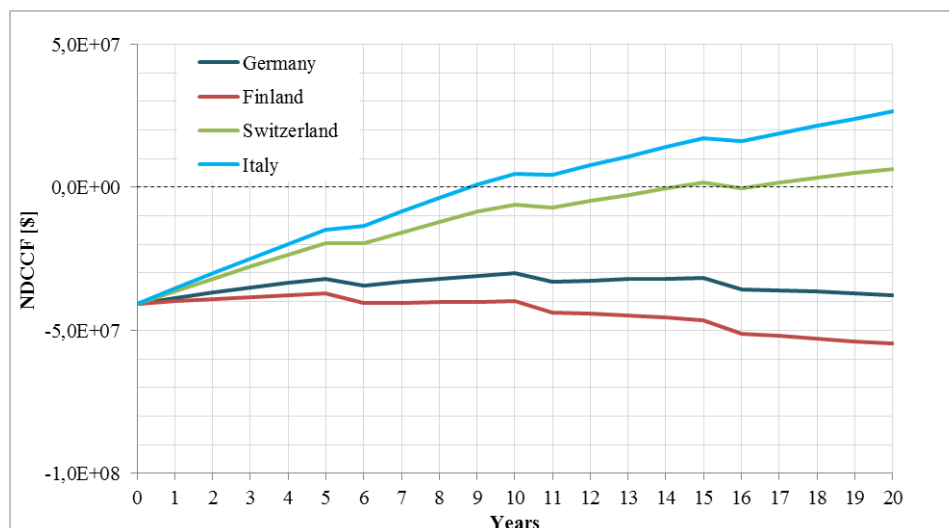


Figure 19. Net discounted cumulated cash flow for the HPR standard case with SOFC mass production.

An assessment of the overall potential for exploitation of gasification SOFC based power production from woody biomass has been developed. For this purpose first of all the overall amount of wood available in Europe has been discussed. Subsequently country specific

characteristics have been analyzed in more detail for Finland, Germany and Switzerland, which are 3 of the 4 countries represented as examples. The maximum achievable impact of application of the technologically and economically most viable system options from Deliverable 5.2 has been assessed, from the technological and economical point of view respectively. In order to present the overall limit of wood exploitation also additional measures to increase the currently available forest potential, and a theoretical 100% energetic utilization of all harvestable wood have been taken into account. It has been found that, from a technological point of view a high share of the total European electricity consumption could be covered using advanced gasification SOFC systems. However, with present day technology maturity and cost structures even at high subsidy levels an economical exploitation of this technological potential is not regarded realizable.

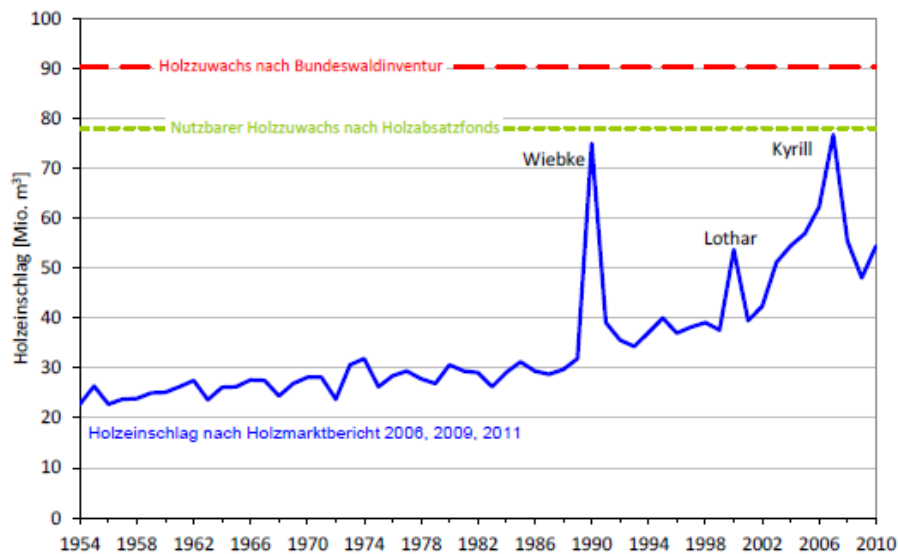


Figure 20. Wood harvested per year in Germany compared to the sustainable limit according to different sources (DBFZ 2013). The peaks in harvestation are attributed to storm wood.

LCA of integrated Gasification plant and SOFC systems

The activity is described in detail on Deliverable D5.4 “LCA of biomass exploitation with the SOFC technology in gasification plants”.

The goal of this work has been to evaluate the environmental performance of a SOFC fuelled with biosyngas from wood biomass and to compare it with traditional technologies (internal combustion engines and micro turbines).

Proof-of-Concept Axis

Design, development and test of the proof-of-concept plant 1 (Italy: 2 kW CHP, WWTU biogas)

Biogas production

The activity is described in detail on Deliverable D6.2 “Installation and operation of the biogas production system”.

The demo is still installed in the SMAT centralized urban (civil and industrial) waste water treatment plant located Torino. Built in 1984, it is the greatest waste water treatment plant in Italy and it serves over 2 million population equivalents in the metropolitan area of Torino

treating over 620.000 cubic meters per day of waste water, with a production of 33000 Nm³/day biogas (2010). In Figure 21 right the top picture of the WWTU plant with indication of the demo siting is shown, while on the left the 3D layout of the demo is represented.

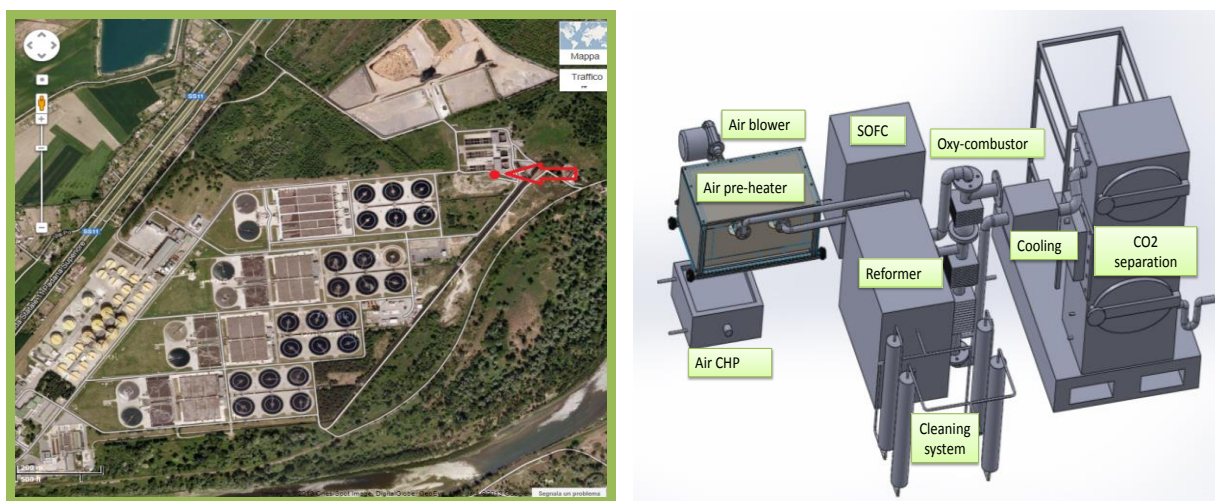


Figure 21. (right) top picture of the WWTU plant with indication of the demo siting; (left) 3D layout of the demo

Biogas cleaning system

The activity is described in detail on Deliverable D6.1 “Basic design for a biogas cleaning system for a first proof-of-concept SOFC system in Torino”.

The cleaning unit is made by two serial vessel containing adsorbent materials. The material choice has been performed after several experimental test in the VTT facilities (Helsinki, Finland). The chosen materials are Zinc Oxide and Activated Carbon for sulphur, halogens and siloxanes removal.



Figure 22. Biogas cleaning unit – frontal view and lateral view.

Biogas processing system

The activity is described in detail on Deliverable D6.4 “Installation and operation of the biogas processing system”.

The biogas reforming unit, developed at CNR-ITAE, can reach a nominal syngas ($H_2 + CO$) production of about $2.5\text{Nm}^3\text{ h}^{-1}$ and is principally based on Steam Reforming (SR) process, but can work also under Oxy Steam Reforming (OSR) reaction through the addition of small amount of O_2 . The reformer, able to operate with biogas produced in an industrial waste water treatment plant, was designed for the integration into a proof-of-concept SOFC system. Preliminary test have been done in the nominal work condition with a simulated biogas ($CH_4=60\%$, $CO_2=40\%$) flow of about 10 NI/min and an H_2O flow of about 725 g/h in SR condition (H_2O/CH_4 ratio between 2-3). Moreover, the unit has been tested also under OSR condition introducing a less amount of O_2 (O_2/CH_4 molar ratio = 0.005-0.25). The oxygen utilization ($O_2/CH_4 = 0.25$) allows to reduce the endothermic nature of the process.

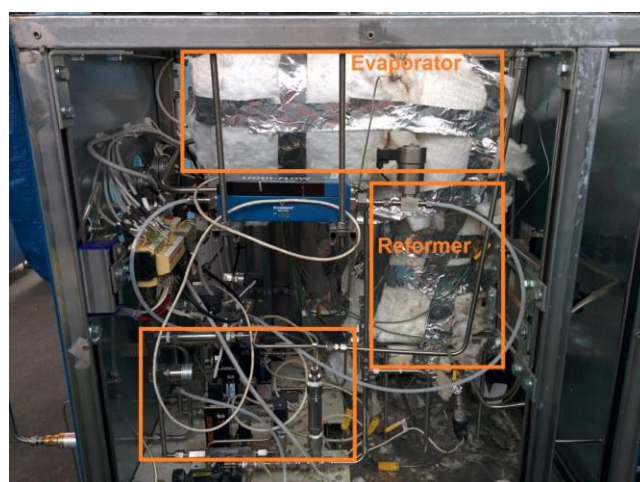


Figure 23. Reformer internal layout.

SOFC CHP system

The activity is described in detail on Deliverable D6.5 “Installation and operation of the SOFC CCHP system”.

The SOFC 2 kW stack has been installed in the Turin Demo Plant during 2014 and has been tested, first indoor in the producer premises and later outdoor. The air side includes the air blower and an air pre-heater (recuperator + electrical). One fundamental issue has been the temperature control within the cell, analyzed in terms of technical solutions as alarm list, HAZOP analysis and installation/test procedure.



Figure 24. SOFC Stack installation.

O₂ separation and anode exhaust catalytic burner

The activity is described in detail on Deliverable D6.6 “Installation and operation of the O₂ separation and anode exhaust catalytic burner”.

The unit has been developed, constructed and operated in laboratory facilities of IEN. After the introductory part of the work, unit was shipped to POLITO for installation and operation as a part of DEMO system in Torino, Italy. Operational characteristics and examples of changes of parameters during tests have been analysed.

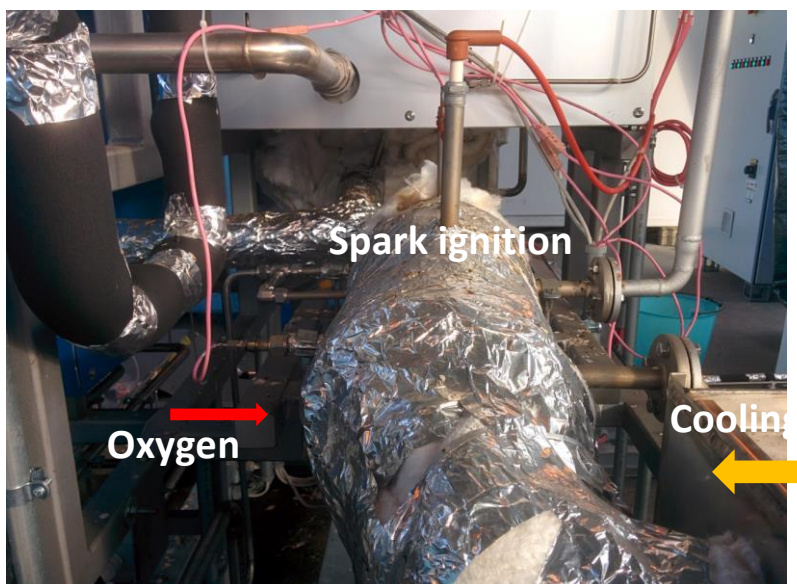


Figure 25. Oxycombustor in the SOFCOM installation at the SMAT wastewater treatment plant.

CO₂ separation from anode exhaust

The activity is described in detail on Deliverable D6.7 “Installation and operation of the CO₂ separation from anode exhaust”.

For water removal from a CO₂/H₂O-containing flue gas of a high temperature fuel cell a two-part device, consisting of a cooler-condenser and a membrane-based system for residual

humidity removal, has been developed, constructed and tested. For calculating the cooler-condenser with its water cooled, cross-flow tube bundle, a thermodynamic calculation model was developed that is taking into account the particularities of partial condensation of an inert gas-steam-mixture. In order to reduce the formation of mist in the cooler condenser, a concept with internal recirculation of condensate was realized.

In the device for residual humidity removal a modified drying membrane, originally designed for drying compressed air, was used in conjunction with an oil-free piston compressor. To control the flow rate, the system works with a closed loop circuit, which allows a largely autonomous operation for integrating the system in a demonstration plant for CO₂ separation. With a specially designed test rig the design calculations could be verified, practical operation of the system could be demonstrated. The gas-steam-mixture, provided by the test rig at similar conditions to the fuel cell exhaust gas, could be dried to a water content of less than 500 [ppm] within a wide range of operation parameters.

At the SOFCOM demo site in Torino the unit has successfully been set up, integrated with the other components and tested.

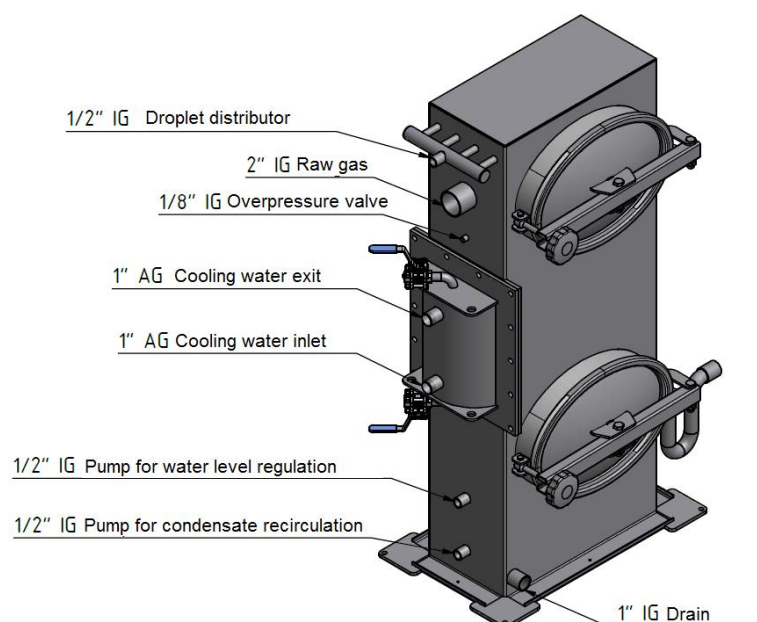


Figure 26. Construction drawings of the condenser housing

CO₂ management and disposal system

The activity is described in detail on Deliverable D6.8 “Installation and operation of the CO₂ management and disposal system”.

A demonstration photobioreactor able to capture up to 1.5 kg CO₂ per day was designed and built. The photobioreactor has a total volume of 150 L and an illuminated surface of 9 m², containing 3 modules of 21 50 mm OD tubes each. Several chemical sensors have been installed for tracking the growing of the algae and the quality of the outlet waste water. The equipment was tested in a Waste Water treatment plant near MATGAS (Barcelona) for 6 month before sending to Torino in order to validate and test the equipment. Test run at 20 mg CO₂/L dose concluded the equipment was able to bio-fix up to 60% of the dosed Carbon

using the nutrients available in the wastewater, being the remaining 40% probably converted into bicarbonate at pH 7.



Figure 27. Front view of the plant with the 3 modules exposed to the sun.

Testing of the complete system

The activity is described in detail on Deliverable D6.9 “Analysis of the specific test session on the complete system”.

The first proof-of-concept SOFC system (Torino, Italy) has been designed, installed, tested for the long run (around 6 months).



Figure 28. Picture of the proof-of-concept in Torino

We have developed specific tests sessions to analyse the behaviour of every single components of the integrated system. Of course, the tests have been developed on all the

complete system working as an integrated plant, but each test session was organized in order to check in particular the performance and behaviour of one single component. As an example, the behaviour of the SOFC stack in case of operation with the slight variable composition of the biogas coming from the digester has been controlled.

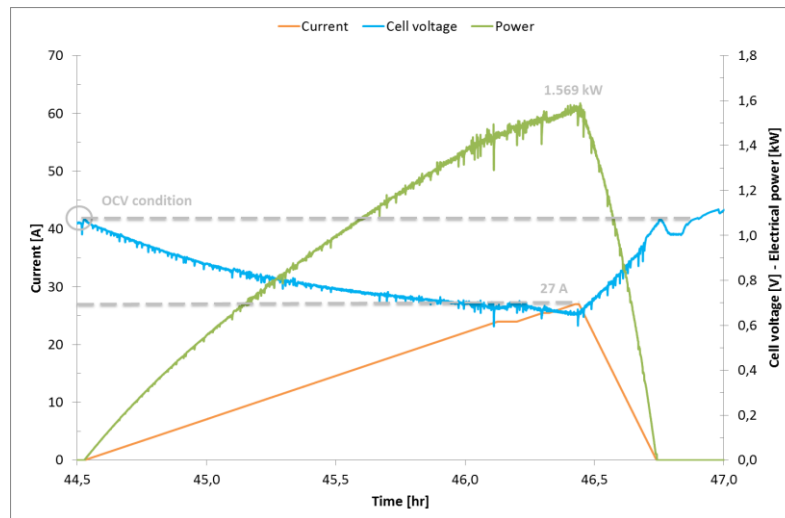


Figure 29. Analysis of SOFC stack power and voltage in variable biogas feeding

Monitoring of the complete system in the long run

The activity is described in detail on Deliverable D6.10 “Analysis of the monitoring on the complete system on the long run” and on the Deliverable D6.11 “Analysis of all the repair and maintenance activities developed on the complete system”.

We have analysed the behaviour of the complete system, and of each single component, during the long time operation, in order to detect degradation and particular behaviour of the system. As an example, here we can see the behaviour of the photo-bio-reactor in a complete month (March 2015), and verify the strict relationship among solar irradiance and production of algae (see turbidity and O₂).

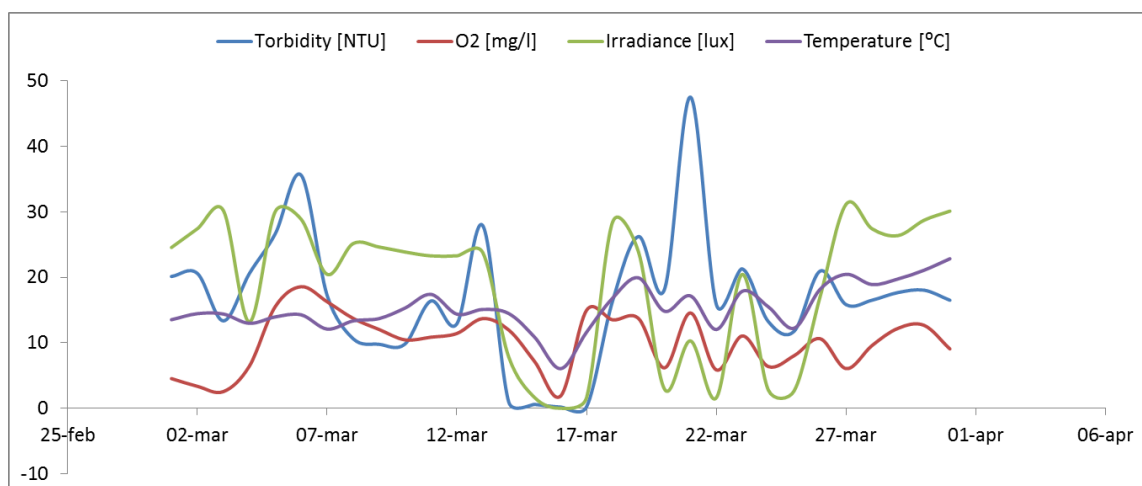


Figure 30. Behavior of the photo-bio-reactor in a complete month (March 2015)

We have also analysed the maintenance activities which have been performed during the SOFCOM demo plant operation in Turin.

The complete list of the maintenance and repair activities has been the starting point for the scale-up guidelines (Deliverable 8.3) which takes into account optimizations of the

components to reduce maintenance costs and times, and for the exploitation plan (Deliverable 9.5).

Design, development and test of proof-of-concept plant 2 (Finland: 5-10 kW CCHP, gasification gas)

Design and construction of the BoP

The activity is described in detail on Deliverable D7.1 “Design and construction of the BoP” and on Deliverable D7.2 “BOP-module of proof-of-concept SOFC system (VTT)”.

The second proof-of-concept SOFC system (Helsinki, Finland) has considered a SOFC stack operating with a syngas from biomass gasification. This demonstration plant has been designed, installed, tested.



Figure 31. SOFC stack module installed and insulated in the in-house proof-of-concept in Helsinki.

Design and construction of the stack module

The activity is described in detail on Deliverable D7.3 “SOFC stack module of proof-of-concept SOFC system (TOFC)”.

The stack module has been design and constructed by Topsoe Fuel Cell A/S (TOFC). The TOFC solid oxide fuel cell stacks are active for the steam reforming and the water gas shift reaction. Therefore, in addition to hydrogen rich fuels, the module can also be fuelled directly with various reformat gases containing methane, hydrogen, carbon monoxide, carbon dioxide and water, thus being suitable for operation with a lean gas corresponding to that from a gasification unit. The module contains four stacks, electrically connected in series, giving a single voltage terminal.

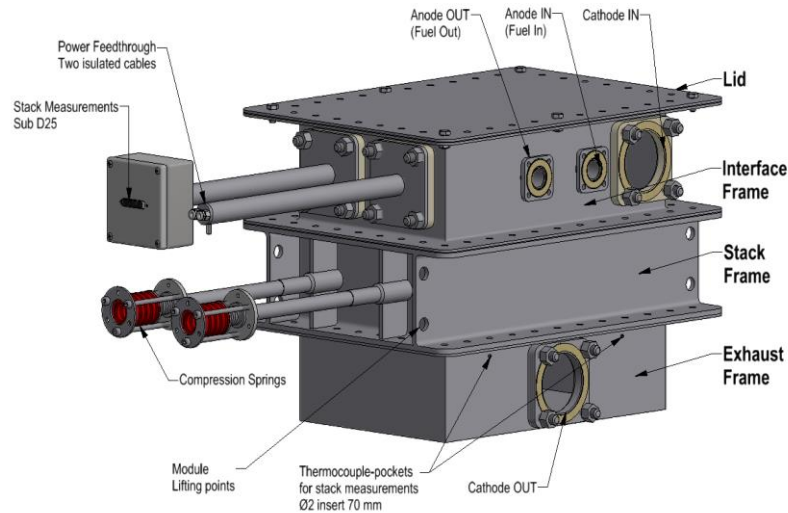


Figure 32. Interfaces and main parts of the stack module

Testing of proof-of-concept system

The activity is described in detail on Deliverable D7.4 “Analysis of the experimental validation of the proof-of-concept SOFC system (VTT&TOFC)”.

The module has been operated for about 1400 h at different operating conditions with different gas compositions as describe in D 7.1. The capability of the system and stack module to performed load cycles has also been tested.

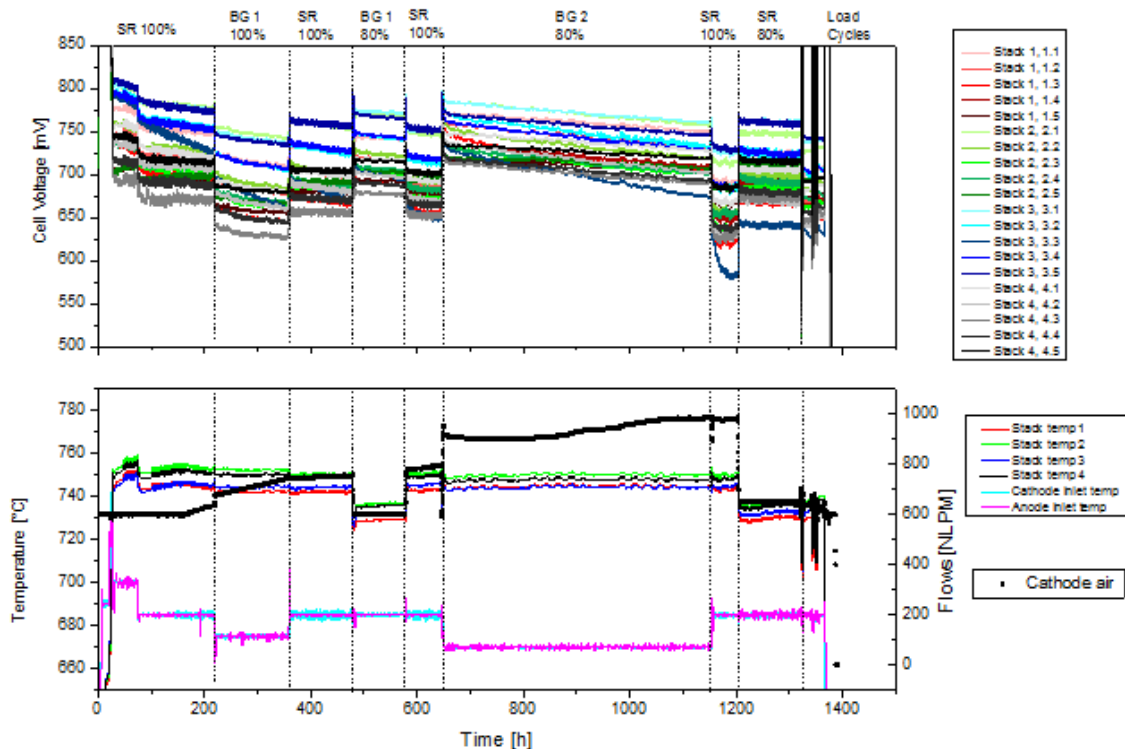


Figure 33. Effect of gas composition on individual cell group voltages (top) and cathode air flow, inlet and stack temperatures (bottom).

Analysis of the results of the demonstration plants (lesson learned): repair strategies; guidelines

Repair strategies

The activity is described in detail on Deliverable D8.1 “Repair Strategies Manual”.

We have developed a summary of the main topic of the repair strategies for the whole SOFCOM demo plant, collected in a Repair Strategy Manual. The Repair Strategies has been developed from the collection of the different components manuals (Deliverable 6.3 to 6.8) and from the analysis of the operation, maintenance and risks related to the overall demo plant.

Monitoring of the complete systems on the long run

The activity is described in detail on Deliverable D8.2 “Operation and Maintenance Manual”.

We have developed a user manual for both the SOFCOM demo plants: the one in Torino and the one in Helsinki. The user manual has been developed from the collection of the different components manuals and from the analysis of the operation, maintenance and risks related to the two demo plants.

Scale-up analysis

The activity is described in detail on D8.3 “Guidelines for the Scale-Up”.

We have analysed the main implementations that would be required for a scale-up of the SOFCOM plant. The SOFC plant scale-up to industrial scale is relatively straightforward as larger stacks are considered. However carbon capture is more critical as a different thermal integration is required compared to conventional systems. In fact, carbon capture through oxycombustion requires a separate management of anode and cathode exhaust. Concerning the re-use of CO₂ in the photobioreactor (PBR) system, a buffer storage volume would be required to account for the nocturnal hours when CO₂ is not required at the PBR. Especially, an improved system for algae removal from the PBR horizontal tubes should be investigated. Algae attachment to the walls of the PBR tubes remains an un-solved issue that should be further addressed in term of hydrodynamics of the flowing water with suspend micro-algae and materials used for the pipes (special coatings on the inner part of the PBR tubes could prevent or reduce the algae attachment).

Pre-normative issues

The activity is described in detail on Deliverable D8.4 “Lessons Learned for RC&S Development”.

We have developed a document dealing with the indications of some lessons learned from the experience done on the whole SOFCOM demo plant which can be useful from the point of view of RC&S.

Potential impact (including the socio-economic impact and the wider societal implications of the project so far) and the main dissemination activities and exploitation of results (not exceeding 10 pages).

Scientific Impact

Objective 1.

Fuel issues considering detailed poisoning mechanisms, advancing in cleaning and processing technologies (done).

Objective 2.

Define and operate new proof-of-concept fuel cell systems fully integrated with biomass processing units and carbon sequestration and handling technologies (done)

Objective 3.

Maintenance, safety, repair and de-commissioning of fuel cell systems on a demonstration scale (done)

In the view of the Project Coordinator, the SOFCOM proof-of-concept is the first in the World demonstration of an innovative systems based on a renewable fuel (biogas in our case) used in the highest energy efficiency process (a SOFC system in CHP configuration), and with a complete re-use of the C atoms in the primary fuel, recovered in form of algae.

From the analysis, the figures are as follows:

- 53.00% of the primary fuel is converted in high value electric power;
- 45.78% of the primary fuel is converted in low grade heat flow, but fully useful in the WWTU plant to supply the heat requirements of the thermo-phillic sewage digesters;
- 1.22% of the primary fuel is converted back in useful biomass, which can be re-inserted in the digester for biogas production, or used for other applications (e.g. bio-fuel productions).

Also, it has to be considered that:

- the biogas is a completely sustainable fuel, produced as a by-product of an industrial activity of treatment of waste waters coming from a Municipality
- the activity performed in the photo-bio-reactor has a practical product which is the cleaning of wastewater streams rich in nitrates and phosphates
- the system provides a complete closed loop of the Carbon atoms; also, the considered C comes from a renewable source (the biogas) and therefore its recirculation could allow a quote of CO₂ emissions from traditional plants fed by fossil carbon. The impacts are now at the local level (where the demonstration is applied) but in principle the impact of these typologies of systems (with complete Carbon reuse) could be at global level once adopted. Every municipality could in principle adopt solutions of circular energy systems demonstrated by the SOFCOM proof-of-concept.

The contribution to the H2020 objectives are several:

- 1) Energy Efficiency: high-efficiency conversion devices represent elements of a sustainable energy portfolio. The SOFCOM proof-of-concept is based on the concept of high efficiency energy transformation.

- 2) Renewable Energy: traditional renewable energy sources (solar, wind and hydro), biogenous fuels (biogas, bio-syngas, bio-fuels) and new synthetic vectors (H₂, synthetic NG). The SOFCOM proof-of-concept makes use of biogenous primary sources.
- 3) Carbon capture and storage: mitigation of CO₂ emissions (related to efficient energy conversion devices, and adoption of RES fuels) and CO₂ recovery. The SOFCOM proof-of-concept applies in practice the concept of complete Carbon recovery and reuse.

Socio-Economic Impact

The second main impact of the project has been the ‘proof-of-concept’ demonstration of two SOFC units integrated with biogas or bio-syngas, respectively. Such fuels have a wide potential in terms of availability and diffusion over the territory. The fuels considered are not only of interest because of their carbon neutrality, but also for certain peculiarities.

In the case of biogas coming from the sewage plant, it represents a by-product of a dedicated process of waste-water treatment. Such plants have already a large diffusion over the territory (especially in urban areas where the continuously collected sewage has to be treated - only in Italy, more than 120 large plants in urban areas exist), with a mature technology already developed behind. Therefore it already subsists a huge biogas potential ready to be exploited, and therefore a large market potential for such SOFC integrated systems. The replication potential is very high. POLITO (Project Coordinator) has worked on a scale-up project, still in Torino (Italy): the application to the FCH2-JU call 2014 (proposal done in November 4th, 2014) has been successful, and we are now preparing the scale up project which foresees the installation of a 174 kW electric SOFC system fed by biogas, the highest size plant in EU so far. We are confident that this scaled-up DEMO will pave the way for a wider adoption of SOFC systems in the sector of biogas, but also in other applications of distributed CHP systems.

The bio-syngas option is another interesting one, investigated within the project, which will face different BoP integration and cleaning issues. Again the market potential of such integrated systems is high, especially for those areas where the biomass feedstock is ready available.

Besides a new application in a scaled-up project, the importance relies in the concept, which is very general and replicable. The concept is the one of complete energy and material recovery (in particular, Carbon recovery) pointing towards a framework of circular economy of energy, with negative CO₂ emissions: the Carbon atom is completely recirculated in the system, and its re-utilization can be looped virtually for an infinite time. The concept demonstrated by the proof-of-concept is completely replicable in similar context, or in completely new context in which the Carbon recovery will become a must. The impacts are now at the local level (where the demonstration is applied) but in principle the impact of these typologies of systems (with complete Carbon reuse) could be at global level once adopted. We think that the social acceptance can be very positive: the idea of system is based on high efficiency use of natural resources, with particular care on the complete CO₂ recovery for Carbon reuse (and not simply for Carbon storage). This can be seen by the Society as a positive concept for the management of energy and its related effects on the global climate.

Cross-cutting issues

Training and Education

In POLITO, Prof. Santarelli is in charge of the MSc Course of “Polygeneration and Advanced Energy Systems”, with more than 200 students each year (course given in English, and so offered also to several Erasmus Mundus students). The SOFCOM project is presented, discussed, and studied every year, with a visit of the students of the proof-of-concept.

Erasmus Mundus II PhD (SELECT+) and MSc (SELECT) in Environmental Pathways for Sustainable Energy Systems. SELECT (www.exploresselect.eu) considers the conversion chain, from primary energy source to final energy service delivered to mankind. The Program is a joint consortium formed by KTH (Royal Institute of Technology, SW), POLITO (Politecnico di Torino, IT), Aalto University (Espoo, FL), TU/e (Eindhoven University of Technology, NL), UPC (Barcelona Tech, SP), IST (Lisbon, PT) and AGH (Warsaw, PL). Many Companies are partners for different activities (Internships, Final Thesis, etc.). The specialization on Fuel Cells is offered by POLITO, with the coordination of Prof. Santarelli. Thus, the SOFCOM project has been strictly related to the activities of the PhD and MSc.

Safety, Regulations, Codes and Standards

One of the principal outcome of SOFCOM is to give inputs to the standardisation activities in the areas related to the operation, management and maintenance of SOFC CHP systems fed by biogenous fuels. The collaboration with RC&S Institutes has been done at the level of the international RC&S institutes: Prof. Santarelli is member of the ISO/TC 197 “Hydrogen Technologies”, IEC/TC 105 Fuel Cells, of the RC&SWG of IPHE.

Some activities of connection with RC&S Bodies have been performed:

1. Prof. Santarelli (Politecnico di Torino, SOFCOM Coordinator) is the representative for Italy in ISO/TC 197 “Hydrogen Technologies”. The last Plenary Meeting was held in Beijing (China) on December 15th, 2011, and Prof. Santarelli has presented and described the SOFCOM project.
2. Prof. Santarelli is one of the representatives for Italy appointed at the IEC/TC 105 Fuel Cells (WG 11 on “Single Cell/Stack Test Methods for SOFC”). The next Committee Meeting will take place in Tokyo (Japan) on October 14-15, 2013.
3. Prof. Santarelli is appointed member of IPHE: he presented SOFCOM activities in the Plenary Meeting in Seville (Spain) in November 15-16 2012.

POLITO, as partner leaded by Prof. Santarelli (Politecnico di Torino, SOFCOM Coordinator) is involved in the FCH JU Project ENEFIELD “European-wide field trials for residential fuel cell micro-CHP” (FCH JU 2011), where he develops the activities related to RC&S of SOFC installation: therefore, synergies between SOFCOM and ENEFIELD on the RC&S issues have been assured.

Main Dissemination Activities

The Dissemination is performed by a web site (www.sofcom.eu, active since M1), a Newsletter, several participation to conferences and invited lectures, and media and press release.

Some examples of Workshops are:

- SOFCOM Kick-Off Meeting held in Torino (Italy) on December 1-2, 2011, an Open Workshop on “SOFCOM Activities and Energy Context” has been held in Torino (Italy)

on December 1st, 2011, with contributions from Massimo Santarelli (Politecnico di Torino, SOFCOM Coordinator) and Jari Kiviahho (VTT, WPs Coordinator). In particular, the Workshop hosted an Invited Lecture given by Prof. Thomas G. Kreutz, Senior Research Scientist at the Energy Systems Analysis Group of the Princeton Environmental Institute (PEI, Princeton University, US), about “A Role for Systems Analysis in Developing Future Energy Systems”.

- In the framework of the SOFCOM M24 Meeting held in Barcelona (Spain) on October 24-25, 2013, a Seminar has been given in MATGAS: Prof. Fausto Massardo, Dean of Engineering School, Università di Genova (IT) “Pressurised SOFC hybrid systems: near term or long term solution?”
- In the framework of the SOFCOM M30 Meeting held in Espoo (Finland) on May 7-9, 2014, a Workshop has been given: “FC systems fed by biogenous fuels: biogas and syngas”, with Invited Speakers:
 1. “Experience with Bio-Gas Fed High Temperature Fuel Cells” Jack Brouwer, University of California, Irvine (US)
 2. “Conversion of wood derived syngas in SOFC systems”, Jürgen Karl, University of Erlangen-Nuremberg (DE)

Some examples of Journal Papers are:

1. B. Tjaden, M. Gandiglio, A. Lanzini, M. Santarelli, M. Järvinen, Small-Scale Biogas-SOFC Plant: Technical Analysis and Assessment of Different Fuel Reforming Options, Energy & Fuels, Publication Date (Web): May 16, 2014
2. Madi H., Lanzini A., Diethelm S., Papurello D., Van Herle J., Lualdi M., Gutzon Larsen J., Santarelli M., Solid oxide fuel cell anode degradation by the effect of siloxanes, Journal of Power Sources, 279, pp. 460-471, 2015
3. Kupecki J., Jewulski J., Motylinski K., Parametric evaluation of a micro-CHP unit with solid oxide fuel cells integrated with oxygen transport membranes, International Journal of Hydrogen Energy, 2015 (in press).
4. F. Curletti, M. Gandiglio, A. Lanzini, M. Santarelli, F. Maréchal, Large Size biogas-fed SOFC Power Plants with CO₂ management: technical and economic optimization, Journal of Power Sources, 2015 (in press)
5. Felix Llovel, Helena Rius, Joaquim Torres, Javier Lafuente and Lourdes Vega, Low cost algae growing by reusing CO₂ and nutrients contained in wastewater, Industrial and Engineering Chemistry Research, 2015 (submitted)
6. H. Madi, S. Diethelm, S. Poatel, C. Ludwig and J. Van herle , Detrimental Damage of Siloxanes on the Performance of Ni- YSZ Anode Supported SOFC, Fuel Cells Journal, 2015 (submitted)

Some examples of International Conferences are:

1. Massimo Santarelli, SOFCOM project, Guest Speaker at the 6 Workshop on Hydrogen and Fuel Cells – WICaC 2012, from October 03 to 05, 2012, at Centro de Convenções - Unicamp, Campinas, SP, Brazil, 2012
2. Olivier Thomann, SOFCOM project overview, Workshop on catalysis & biogas, Stockholm, Sweden, 2012
3. Marta Gandiglio, Andrea Lanzini, Massimo Santarelli, Design and balance of plant of a demonstration plant with a solid oxide fuel cell fed by biogas from waste water and exhaust carbon recycling for algae growth, ASME 2013 7th International Conference on Energy Sustainability & 11th Fuel Cell Science, Engineering and Technology Conference ESFuelCell2013, held in Minneapolis, MN (USA) on July 14-19, 2013. The paper has been awarded of the Best AESD Student Paper 2013 Award.

4. Massimo Santarelli , SOFCOM Project: Proof-of-Concept of WWTU Plant Feeding a SOFC CHP System Integrated with CO₂ Removal, 13th International Symposium on Solid Oxide Fuel Cells (SOFC-XIII), Okinawa (Japan) on October 6-11, 2013.
5. Hartmut Spliethoff, "Gasification - the key for efficient power generation", at the 2nd INTERNATIONAL SYMPOSIUM - Solid Oxide Fuel Cells for Next Generation Power Plants: SOFC's & RENEWABLE ENERGY, London April 19th, 2013
6. Massimo Santarelli, SOFCOM project, invited speaker in ICEPAG 2014 (Newport Beach, CA, US) in April 2014.
7. Massimo Santarelli, SOFCOM project, invited speaker in the 3rd International Symposium on Solid Oxide Fuel Cells for Next Generation Power Plants (Warsaw, Poland) in May 2014.
8. Andrea Lanzini, SOFCOM project, invited speaker in the Workshop Progress in Fuel Cell Systems (Bruges, Belgium) in May 2014.
9. M. Santarelli, J. Kiviaho, R. Singh, L. Meucci, L. Vega, V. Chiodo, J. Jevulski, S. Herrmann, SOFCOM Project: analysis of the SOFC DEMO plants in Torino (biogas), 11th European SOFC Forum 2014, held in Lucerne (CH) on July 1-4, 2014.
10. Joaquim Torres, Javier Lafuente, Lourdes F. Vega and Massimo Santarelli, SOFCOM: Pilas de combustible de óxidos sólidos, Operación y Mantenimiento, Congreso Iberoamericano de Hidrógeno y Pilas de Combustible – Barcelona October-2014
11. Markus Rautanen, Biomass to SOFC – selected results from SOFCOM project, 7th Workshop on progress of fuel cell systems, Brugge, Belgium, 2014
12. Massimo Santarelli, Poly-generation system based on biogas-fed SOFC plant, with production of heat & power, microalgae and cleaned water: the SOFCOM proof-of-concept, KOREA-ITALY Bilateral Symposium Hydrogen and Fuel Cells: Current Issues and Perspectives, Korea Institute of Science and Technology - Seoul, Korea, April 21st~22nd, 2015
13. M. Santarelli, A. Lanzini, M. Gandiglio, Electrochemical systems for a circular energy economy and carbon reuse, Our Common Future Under Climate Change, International Scientific Conference, 7-10 JULY 2015 Paris, France
14. H. Madi, S. Diethelm, C. Ludwig and J. Van herle. Effect of Toluene on the performance of SOFC. Proceeding of SOFC symposium 2015 Glasgow.

The main Press Releases are:

1. Article in "International Innovation" for SOFCOM dissemination (October, 2012)
2. Two pages full colours dissemination papers in European energy Innovation magazine - Prologue Media Ltd (spring 2013 issue)
3. Tutto Green, article devoted to disseminate the FCH technologies in industry and to inform people on the FCH adoption in Industry - LA STAMPA (daily news-paper Italy)

Main Exploitation Activities

The Exploitation Plan deals in particular with a fundamental point related to every research activity: what's next? The objective of the project is in fact not only the achievement or not of the initial objectives but also, depending on the demonstration results, the definition of a future activities plan. If the technology has been demonstrated to be as efficient as supposed, the exploitation plan should focus on the technological transfer from the research area to the real industrial market. Each partner involved, starting from the experience achieved during the SOFCOM project, has thus analysed the potential of the technology and proposed a valid exploitation plan for the future decades.

The final objective of each research activities is the “real world” and market penetration, moving the demonstrated technologic advantages of an object from the laboratory scale to the everyday life scale.

For what concerning the SOFCOM project, the main objective is related to the industrialization of the SOFC concept, because of its high efficiency, low emissions, high modularity, etc.. The experience of a wide and long project such as the SOFCOM one, has brought every partner to analyse the work done and make plans for the future depending on the achieved results.

The list of each partner exploitation plan is presented in the Deliverable D9.5 “Final Report on exploitation and dissemination achievements”. Each section presents the motivations for the exploitation plan, the definition of the plan, strength and criticalities of the proposed idea and future activities.

Motivation for the exploitation plan

The exploitation plan concept is growth, together with SMAT, analysing the potential of the SOFC system in a biogas plant. As well known, SOFC are direct competitors of the traditional Internal Combustion Engines (ICE), which are the most common installation in a biogas plant. SOFCs show visible advantages respect to ICEs (higher efficiency, zero emissions, low O&M cost), but the still high investment cost is still acting as a barrier for real industrial installations. ICE are indeed a well-known technology, developed since lots of decades, and thus their investment price is relatively low.

Analysing the existing biogas plants, two different scenario can be found:

- Small size biogas plants (hundreds of kW) fed by local resources from the owner’ land or company.
- Large size biogas plants (> 1 MW) fed by one or more than one substrates collected in the nearby area from different companies.

ICEs are a currently good investment for what concerning large size plants since they have real competitive investment cost (< 1’000 €/kW) and acceptable electrical efficiencies (40-43 %). Emissions are still a problems, often “solved” using a post-combustor fed by external NG to respect emission limits by law. In this large size market area, SOFC penetration should be driven by a reduced investment cost and thus a better economic profile.

The scenario is different for the small biogas plants: here ICEs are more expensive (cost is not linear with size!) and low efficient (electrical 35-38%, thermal 20-30%). This has been identified as the first possible market for SOFC, where ICEs are not so competitive and the only available alternative is a simple boiler for thermal production.

The main topic of the exploitation plan, developed by POLITO, includes:

- Motivation: analysis of existing fuel cells and SOFC market
- The new DEMOSOFC EU project: detailed description of the exploitation plan, focus on some components of the scaled-up plant: pre-thickening system, heat-exchanger for thermal power recovery, efficiency map and techno-economic evaluation results
- Advantages and criticalities of the SOFC concept
- Opportunities for the SOFC technology, subsidy schemes

Main outcome of the exploitation plan

A new EU project, named DEMOSOFC, related to a scale-up of the SOFC concept at industrial scale, has been accepted and will start on September 1st, 2015.

The proposed project foresees the demonstration of an integrated digester gas-fed SOFC plant at a scale relevant to industry. A 174 kWe SOFC plant consisting of three modules (each rated 58 kWe) will be installed in the wastewater treatment plant of Torino Collegno-Pianezza (IT) producing the biogas fuel. The WWTP currently serves 270'000 equivalent inhabitants – a portion of the overall municipality of Torino – thus collecting an overall of 59'000 m³ of wastewater on a daily basis that corresponds to ~220 liter/day/capita. Digester gas is available from the anaerobic fermentation of pre-thickened sludge at this facility. The suspended solid volatile (SSV) fraction in the sludge results in 1.34 wt. % leading to a biogas yield of 0.39 Nm³ of biogas per kg of SSV. Given these site-specific productivity facts, and by taking the biogas-to-electricity efficiency of 53% (LHV basis) for the SOFC generator, the resulting electricity yield is ~1 We/capita.

The SOFC plant will be installed in the SMAT Collegno WWTP (Waste Water Treatment Plant), in the Turin area, and will guarantee the supply of around 30% of the site electrical consumption, and almost 100% of the thermal requirement.

The DEMOSOFC plant will be the first example in Europe of high efficiency cogeneration plant with a medium size fuel cell fed by biogas.

DEMOSOFC partnership includes, besides SMAT and Politecnico di Torino, the Finnish fuel cell manufacturing company Convion Oy and the Finnish research center Teknologian Tutkimuskeskus VTT, together with the Imperial College of Science, Technology and Medicine (UK).

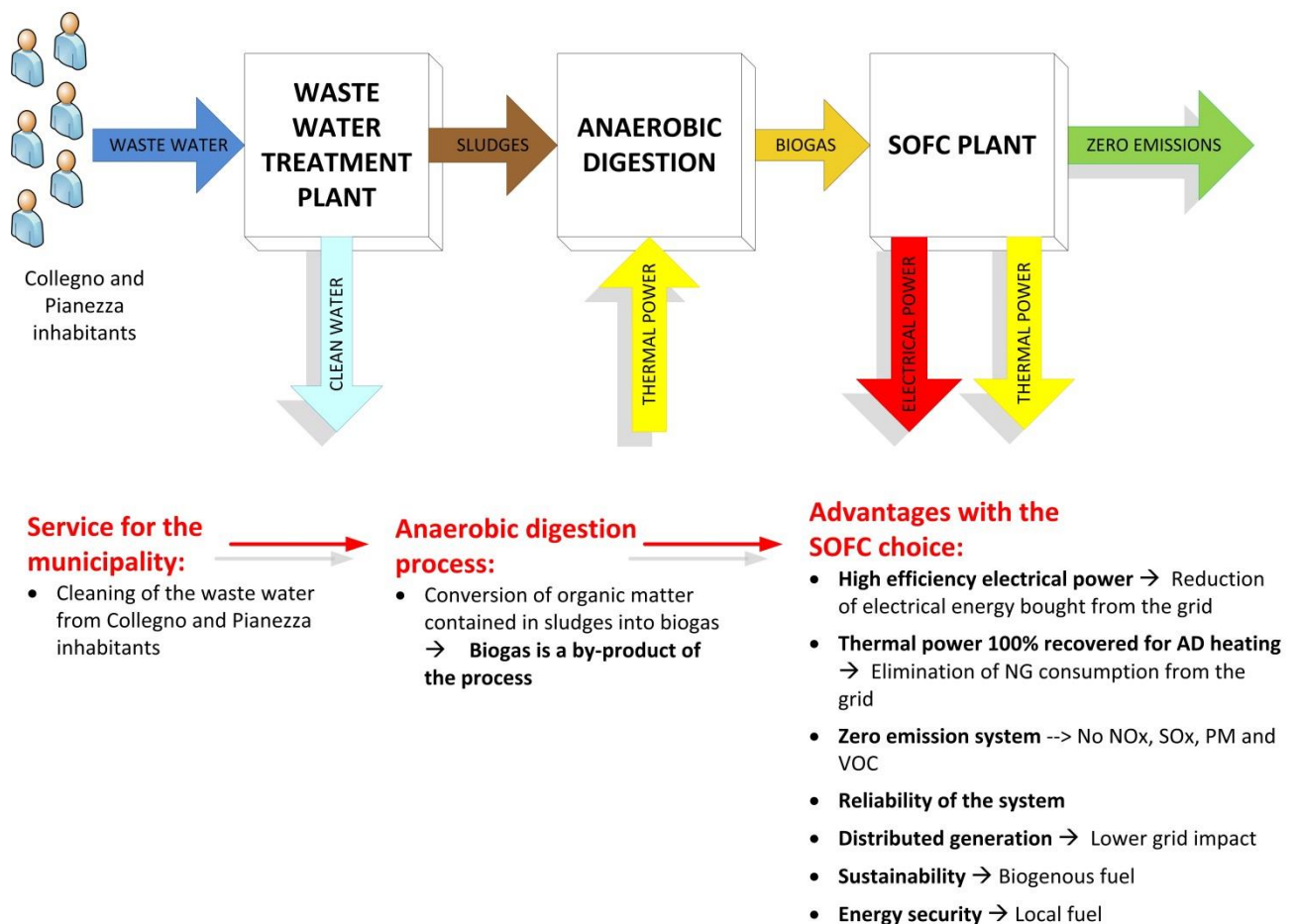


Figure 34. Concept of DEMOSOFC project

The DEMOSOFC concept is presented in Figure 35. A distinctive feature of the integration of the SOFC within a WWTP is that both the electricity and heat produced are used onsite. Electricity consumption in the plant is generally higher than the electricity output from biogas as several pumps, compressors and other mechanical devices are in operation within the WWTP to process the wastewater. Looking instead at the thermal balance, the waste heat available from the SOFC can be almost fully recovered by pre-heating the sludge feeding the digester: this is a necessary step of the process, and the heat recovery from the SOFC allows the total substitution of external natural gas (fossil fuel consumption). Any surplus heat from the SOFC (generally available during the summer) could be exploited for other uses (e.g., domestic hot water in urban district heating loops).

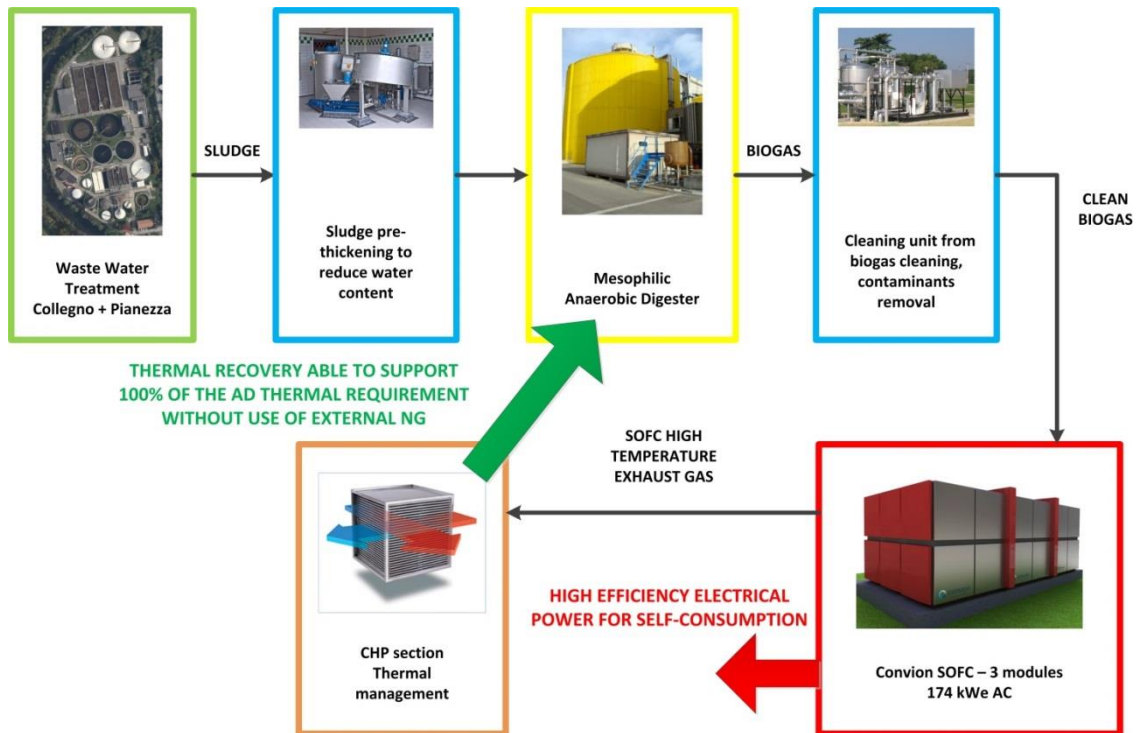


Figure 35. Schematic concept of the DEMOSOFC installation

A preliminary economic analysis of the installation has been done.

Regarding the cost related to the stack replacement (always thanks to the data provided by Convion): the value of 20% is very low if compared with the present costs that can reach 80% of the initial cost of the system, but also in this case a target value of 30% have been assumed and a comparison with different percentage of costs is presented.

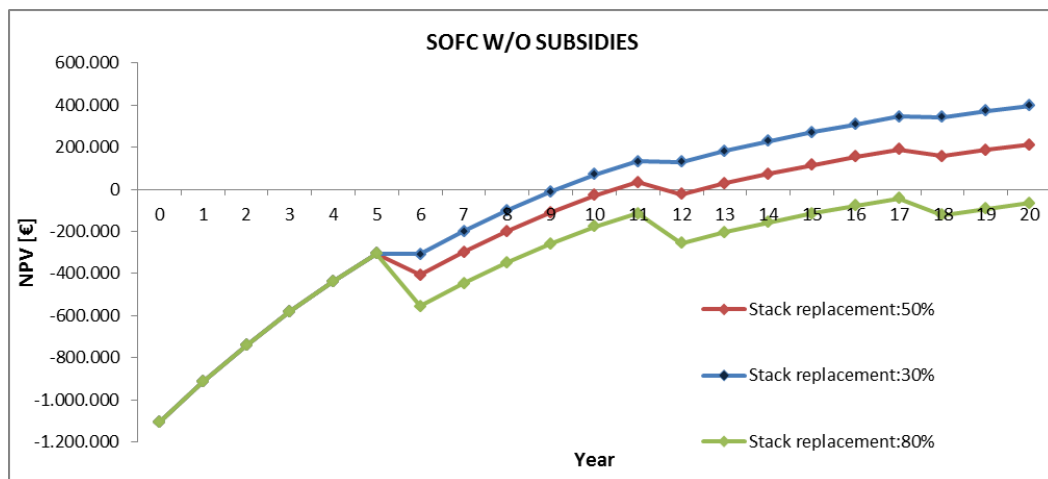


Figure 36. NPV evolution with different stack replacement costs

It can be noticed how the cost of the replacement affects the return of investment: its influence is of small incidence when we pass from 30% to 50%, but if we consider the current cost of replacement provided by Convion, this parameter can frustrate the goodness of the investment. That's the reason why the decrease of the specific cost of installation is desirable: in fact the drop of this quantity affects in a positive way also the cost of replacement (and thus the specific cost of production) of the stack.

Regarding the initial cost of the system, thanks to a direct contact with a partner of the SOFCOM project, a more precise estimation of the specific cost of the SOFC has been implemented. Convion is, at the moment, one of the few European subjects that is planning to produce this kind of systems (of this size) and for this reason the price of production is very high. But a target price of production in the next years have been provided, and used in this simulation, equal to 3.500 €/kW.

Keeping fixed the value of stack replacement (to 30%), in the graph below the evolution of NPV with different initial costs (+/- 50% referred to the target cost considered above) is reported.

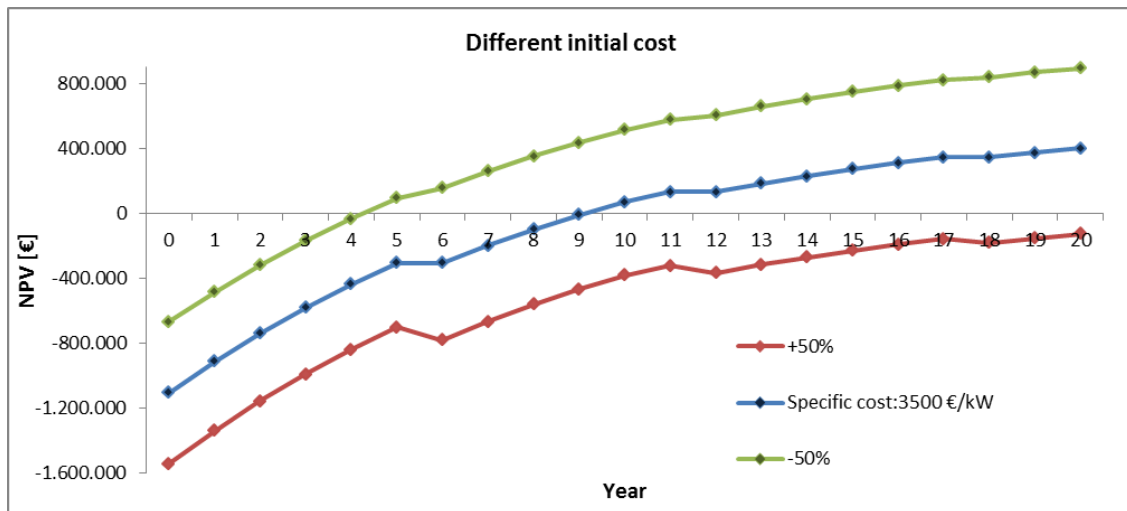


Figure 37. NPV evolution with different initial stack specific costs

This figure tells that the technology considered, at least for the size chosen here, will be attractive for the companies of this sector only when the costs associated to this system will be halved thanks to scale production of the components. The increase of the target cost clearly leads to a negative NPV at the end of the period considered, thus making the investment not profitable.

Address of the project public website, if applicable as well as relevant contact details.



Project website www.sofcom.eu

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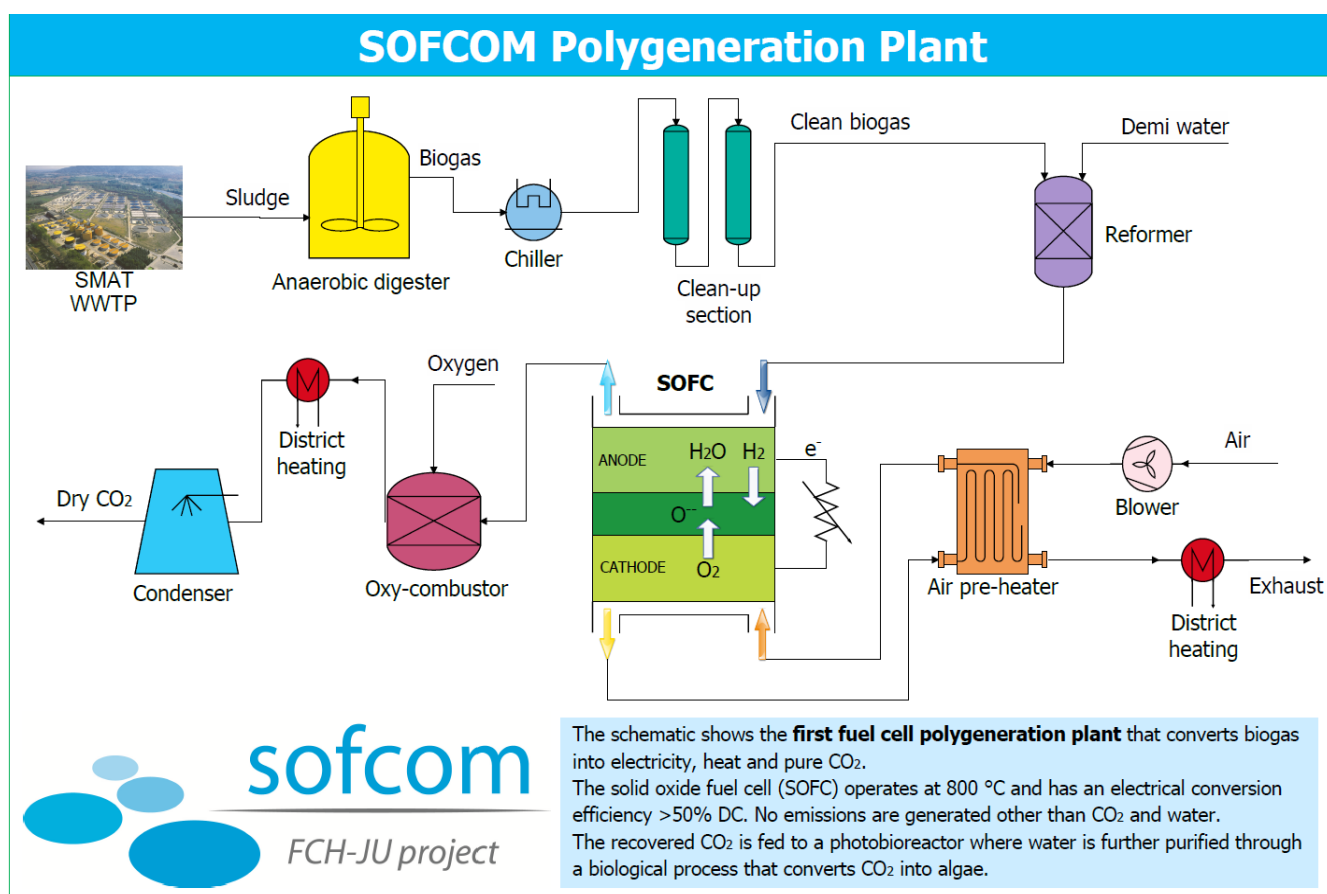
Marta Gandiglio (marta.gandiglio@polito.it)

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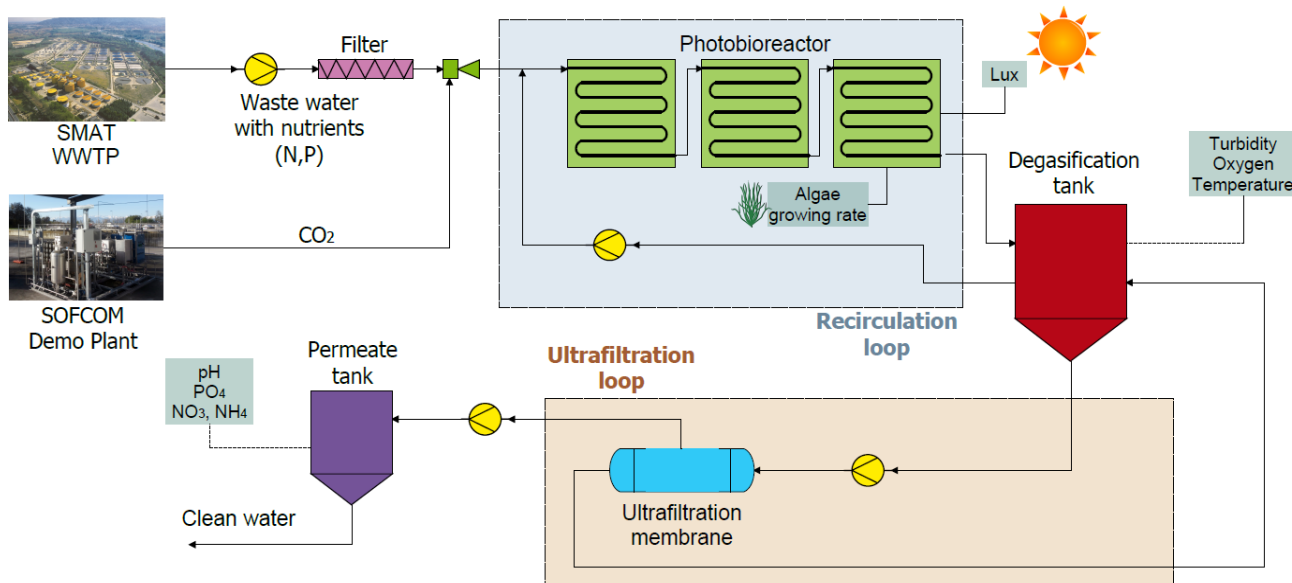
Furthermore, project logo, diagrams or photographs illustrating and promoting the work of the project (including videos, etc...), as well as the list of all beneficiaries with the corresponding contact names can be submitted without any restriction.

VIDEO ON YOUTUBE

<http://youtu.be/sk7lwhBoU8w>



SOFCOM Photobioreactor Plant



The schematic shows the photobioreactor plant that converts the waste water flow into clean water fixing the CO₂ exhausted from the SOFC system plant into algae through the photosynthesis process.

SOFCOM Demonstration Plant



SOFCOM Demonstration plant





Picture of the SOFCOM DEMO



Photo-bio-reactor for Carbon fixing in micro-algae