DEMOSOFC

Project n° 671470

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

Deliverable number 2.4

Detailed engineering of the DEMO

(Task leader: SMAT - Participants: CONVION, VTT - Start: M3 - End: M6)

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Abstract:

The document includes details on the DEMOSOFC plant blueprint. In particular, technical drawings and descriptions are given for the following areas:

- ✓ General plant footprint and General system layout
- ✓ Inlet and outlet stream specifications
- ✓ Description of single units: clean-up section, SOFC modules and thermal recovery
- ✓ Electrical system definition
- ✓ Control system definition

Keyword list: biogas, SOFC, WWTP, blueprint, design, layout, electrical system, control system,

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1. Process description

The DEMOSOFC plant will be the first biogas fed industrial size SOFC installation in Europe. The system will be installed in an existing municipal Waste Water Treatment Plant in Collegno, Turin (IT). Biogas is currently produced in an anaerobic digester from sludges, by-product of the water treatment line. In the current scenario, biogas is burned into a traditional boiler and heat is exploited for the digester heating (digester is kept at ~ 42-43 °C).

The new DEMOSOFC installation will consist of three main sections:

- Biogas processing unit, where biogas is compressed, dehumidified and cleaned from harmful contaminants (sulphur, silicon).
- SOFC modules, where electrical power is produced and used for the WWTP internal needs (around 30% of the plant electrical consumption will be covered by the new DEMOSOFC plant). Three modules, able to produce 58 kWe each, will be installed.
- Heat recovery section, where thermal power contained in the exhaust gas is recovered in a water-gas heat-exchanger (placed inside the module) and transferred to the sludges entering the digester (in a secondary water-sludge heat-exchanger).

Figure 1 shows an aerial view of the Collegno WWTP. Water lines can be seen on the top and center of the pictures. The digester is located on the bottom left side, together with the gas holder. Currently two digesters are available on site but only one is on operation because of the limited sludge amount. A second digester, currently not in operation, is also present. Future feedings of the system with sludges from other WWTPs could require the second digester to be started.

Figure 1. SMAT Collegno WWTP. Aerial view.

The SOFC module, provided by the Finnish company and partner of DEMOSOFC, Convion, is shown on Figure 2.

The system will be fed by 57.9 m^3/h of biogas for the three modules, with an average methane content of 63%.

The plant will be installed in a new concrete basement inside the WWTP. A new technical building will also be erected for the electrical cabinets, the water pumps and the control room.

Figure 2. Convion SOFC module, able to produce 58 kWe.

Concerning the technical building, the structure consists of steel supporting frame, corrugated metal roof, insulated external walls in insulated corrugated sheet (one side) and glass façade (three sides).

Two windows will be included, of openings minimum size 180 cm (L) x 220 (H) and two minimum size 90 cm (L) x 220 (H), of which one with a glass.

2. **Site layout & required infrastructure (3D)**

The DEMOSOFC infrastructure will be all contained in the red area shown in Figure 3. Zooming on the red area (Figure 4), the biogas currently available lines are shown (yellow), together with the biogas storage system (gas holder) and the current boiler room. The DEMOSOFC site area has also been defined.

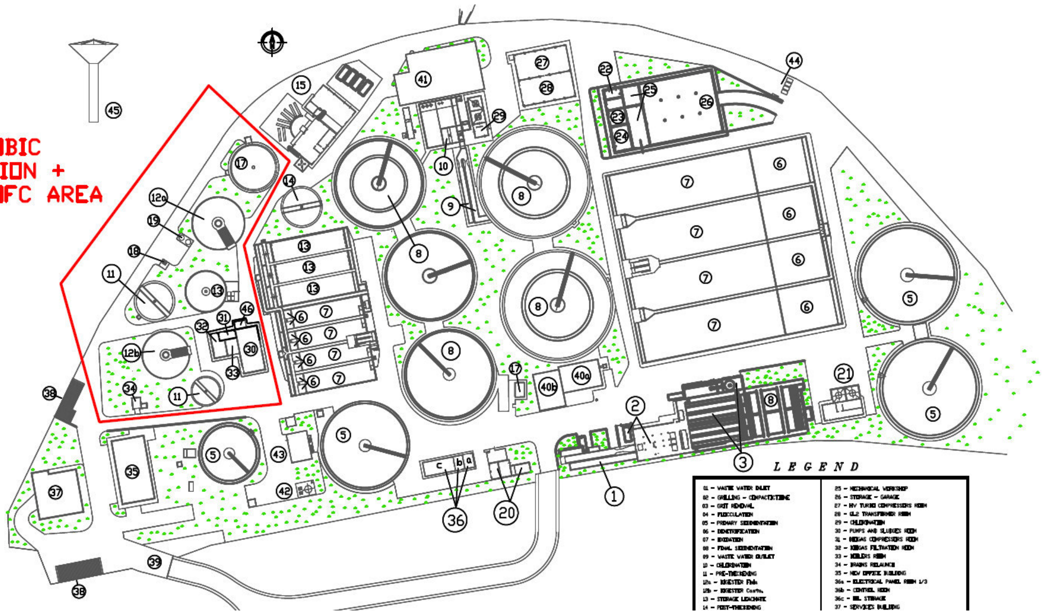


Figure 3. Collegno WWTP layout and DEMOSOFC area.

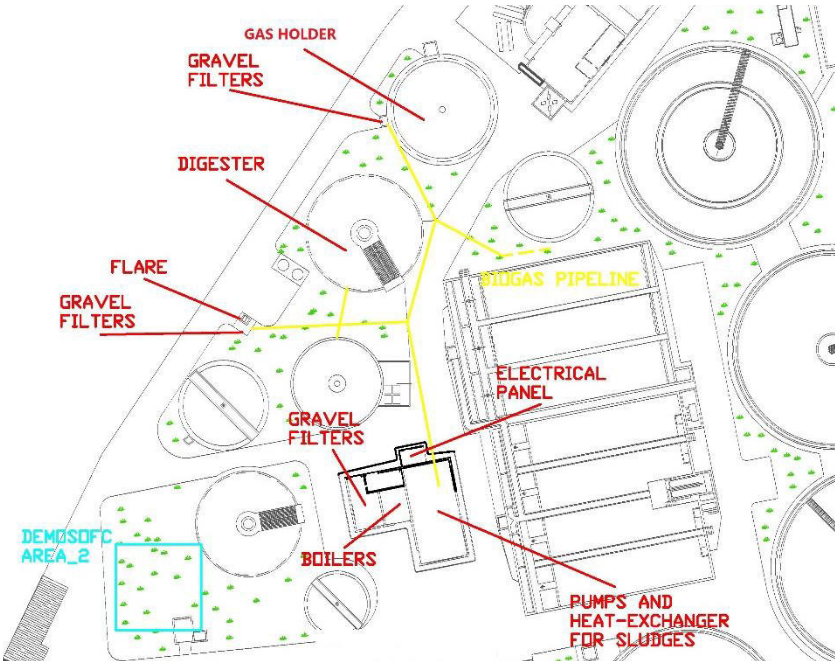


Figure 4. Biogas production an DEMOSOFC area.

Starting from the available connections and the area for the new installation, the system design has been developed. 3D sketches are shown in Figure 5 and Figure 6. The technical building is the one with glass windows on the sides. Here the control room will be placed, together with the conditioned electrical cabinets room and the water pump for thermal recovery room .

The biogas conditioning system, including both compressor, chiller and contaminants adsorption system will be placed inside a container (on the right in Figure 5). The container solution has been preferred to other because of safety reason (the supplier will certify the entire clean-up section as a unique product) and in order to have a conditioned area (heated/cooled) for biogas processing.

The three SOFC modules will be placed outdoor, in a dedicated area, and will be fed with biogas from the clean-up unit.

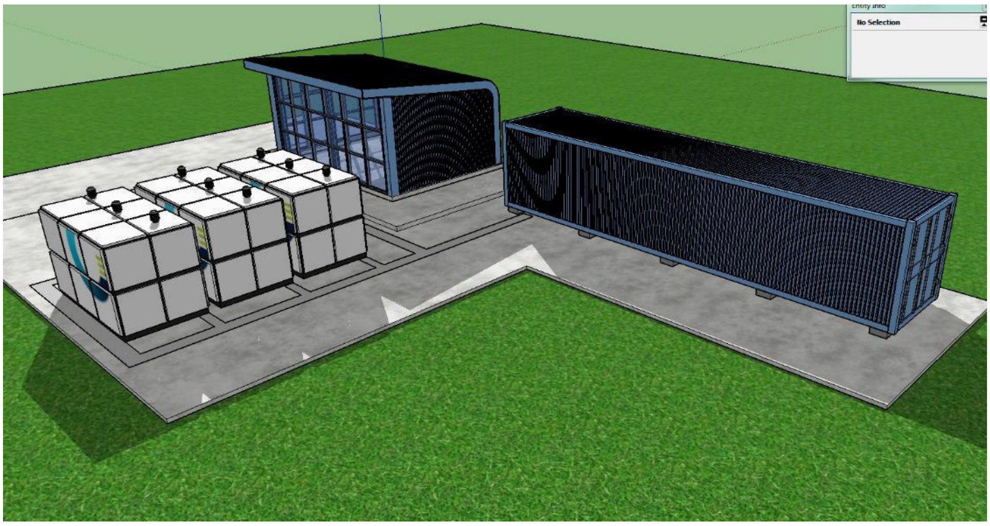


Figure 5. DEMOSOFC plant 3D sketch.

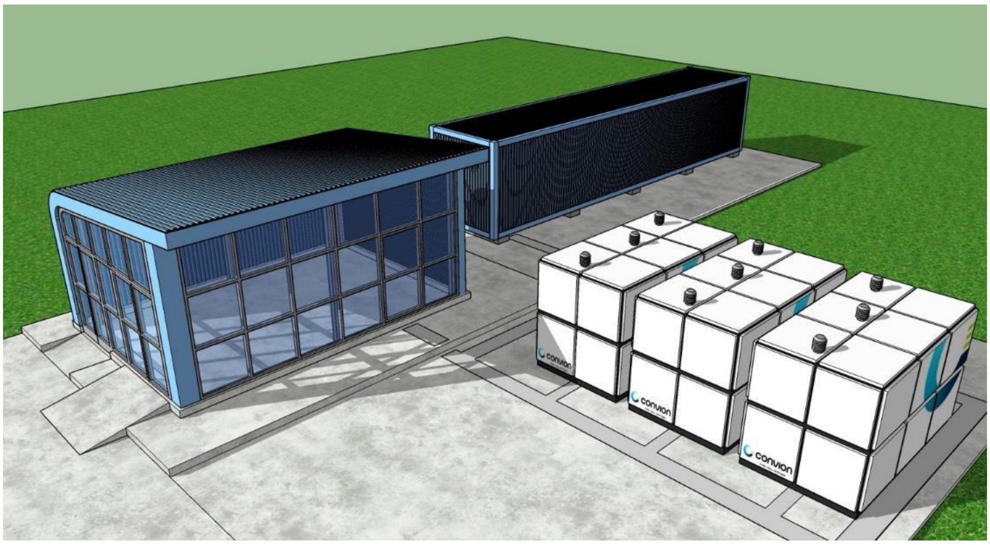


Figure 6. DEMOSOFC plant 3D sketch.

The area of intervention is shown in the attached technical drawing "*AREA DI INTERVENTO – PIANTE E PROSPETTI*" (Appendix A). Here, on the top, the aerial drawing is shown with connections cables and pipelines from the clean-up to the SOFC modules and from the SOFC modules to the technical building. On the bottom, the side views are shown. On the right, the general DEMOSOFC layout, more detailed in the second technical drawing "*PLANIMETRIA GENERALE IMPIANTI E LINEE – AREA DI INTERVENTI*" (Appendix B).

Electrical cables, heat recovery and gas lines are shown on Figure 8.

Biogas (blue line), as will be discussed later, will reach the DEMOSOFC area from the gas holder. In between, biogas will be send to a blower and a chiller, in order to have enough pressure to reach the compressor inlet and to avoid water condensation. Through an outdoor insulate pipe rack, biogas will reach the container where the clean-up system, together with a compressor and a chiller, is placed. From the container outlet, biogas is then sent to the three SOFC modules and the lines is thus splitted. Manual on/off valves on each feeding line will guarantee the possibility to work with less than three modules in operation. Difference between continuous and dashed blue lines are due to a change in the pipe diameter because of biogas changing pressure (existing lines are continuous, dashed are new construction).

Water line (orange) will be sent to the SOFC modules to recover thermal power from exhaust. In the technical buildings (pumps room) water is then pumped to the sludge-water heat-exchanger, placed in a different area of the plant (sludge pump room), as will be discussed later.

Electrical cables (pink) are going from the modules to the electrical cabinet room inside the technical building, where transformers and grid cabinet interfaces will be place. SMAT main electrical cabinet, connected to the grid at medium voltage, is instead placed in a different area.

The layout of the technical building is shown on Figure 7:

- <u>Control room</u>: the room contains a desk (working position), a monitor display for showing main results and plant layout to visitors and the general PLC of the system.
- <u>HRU pumps room</u>: here the circulation pumps for the heat recovery unit (HRU) are contained. The internal room layout is still under development.
- <u>Electrical cabinets room</u>: the room will include 3 power conditioning cabinets (one per each Convion module), one grid interface cabinet for the three modules, a UPS and a transformer (TRAFO) system installed by SMAT, which will be discussed in the electrical section and two SMAT cabinets for the whole system management (Switches cabinet and services el. cabinet). The Convion modules transformer is place outside the room in an outdoor position, being an IP54 system.
- <u>Gas analyser</u>. The gas analyser will be placed outdoor in a conditioned cabinet provided by the supplier of the system. The choice of an outdoor installation is due to safety issues, since gas is treated inside the system. The position of the cabinet, even if in the drawing is close to the technical building, will be as close as possible to the sampling points (placed inside the container).

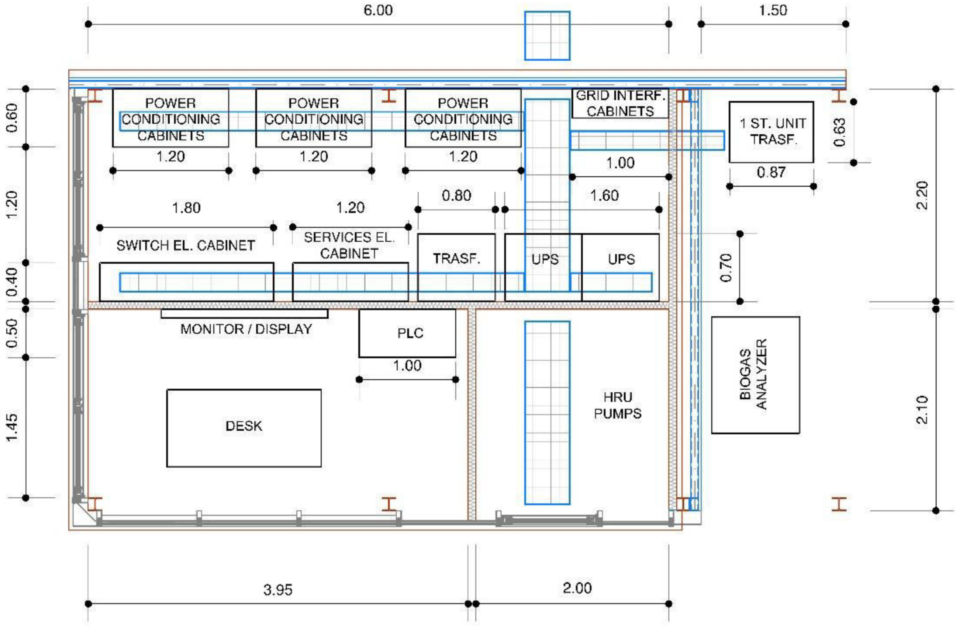


Figure 7. Technical building layout.

As discussed above, part of the system (biogas chiller and blower, sludge-water HX) will be placed in different areas of the plant. Their layout is shown on the technical drawing "*PLANIMETRIA GENERALE IMPIANTI E LINEE LOCALE POMPE FANGHI ESISTENTE – OPERE IMPIANTISTICHE*" (Appendix C). The same building, called "sludge pumps room/building", is shown on the left without the roof to underline the internal layout and on the right with the roof to show the biogas pipeline placed there.

Analysing the internal layout, the sludge/water heat-exchanger can be seen on the top right side of the drawing (HRU-04) fed by the water from the DEMOSOFC area (orange line) and by the sludge, which connections (inlet and outlet) are shown in the same room with brown lines. Industrial water (light blue line) is also available and connected to the HX to remove the heat in case sludge cannot be fed to the system. Finally biogas pipe (blue line) can be seen on the roof; the dashed pipe is referred to an existing pipe, which will be extended with the continuous line through a pipe diameter reducer.

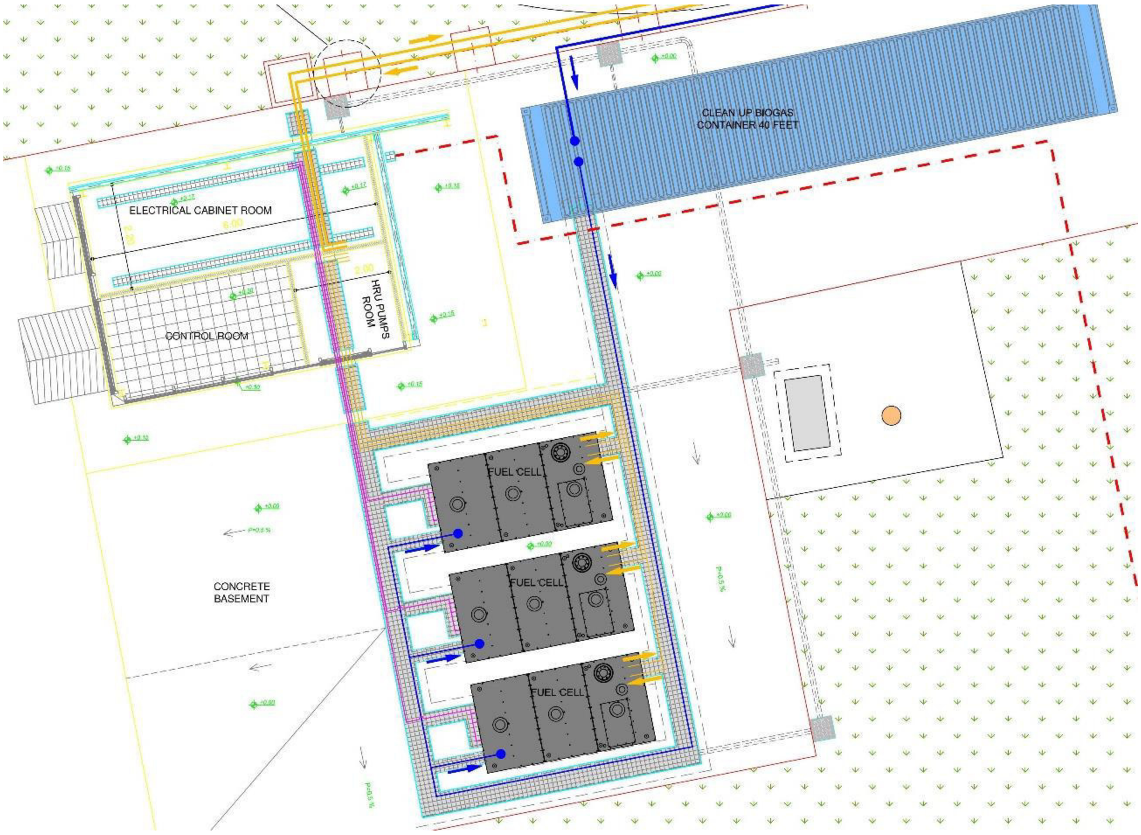


Figure 8. DEMOSOFC plant general layout.

In order to resume the DEMOSOFC plant concept and its integration with the existing WWTP, a schematic of the system is shown on Figure 9:

1. Sludges are fed to a gravitational pre-thickening system and then splitted among the new HX (fed by the DEMOSOFC heat recovery) and the existing HX (fed by the gas boiler). The sludge fed to the boiler is also mixed with a recirculation flow from the digester (sludge recirculation line), before being fed to the HX. The two pre-heated streams are then mixed and sent to the first (and unique in this scenario) anaerobic digester.
2. First outlet stream from the anaerobic digester are digested sludges. The streams can be fed either to the secondary digester (currently not in operation) or to a post-thickener. Sludges are then dried in a de-hydration system.
3. Second outlet stream from the digester is the biogas. A biogas recirculation loop from the top of the digester to the bottom is used to mix the sludge into the digester in order to keep the reactions and the temperature as stable as possible. The biogas outlet stream is indeed send first to gravel filters and then to a desulphurization system, before being stored in the gas holder.

4. From the gas holder, biogas can be fed to the boiler, as in the current scenario, or to the DMEOSOFC site, or to the flare in case of digester too high level or emergency.
5. In the DEMOSOFC area biogas is cleaned, de-humidified and compressed, and then fed to the three SOFC modules. Hot water is produced in three exhaust gas-water HX and sent back to the water-sludge HX described before.

The same process, from sludge to biogas to hot water can be seen also on the map in the technical drawing "*P&ID GENERALE DEGLI INTERVENTI – OPERE IMPIANTISTICHE*" (Appendix D). In the document, the following existing components can be underlined:

- 11. Sludge pre-thickener
- 30. Sludge pumps and HX
- 12a. First anaerobic digester
- 12b. Second (not in operation) anaerobic digester
- 17. Gas holder
- 32. Biogas gravel filter
- 19. Desulphurization system
- 33. Gas boiler
- 18. Gas flare

The DEMOSOFC area is represented with red boxes on the bottom of the drawings.

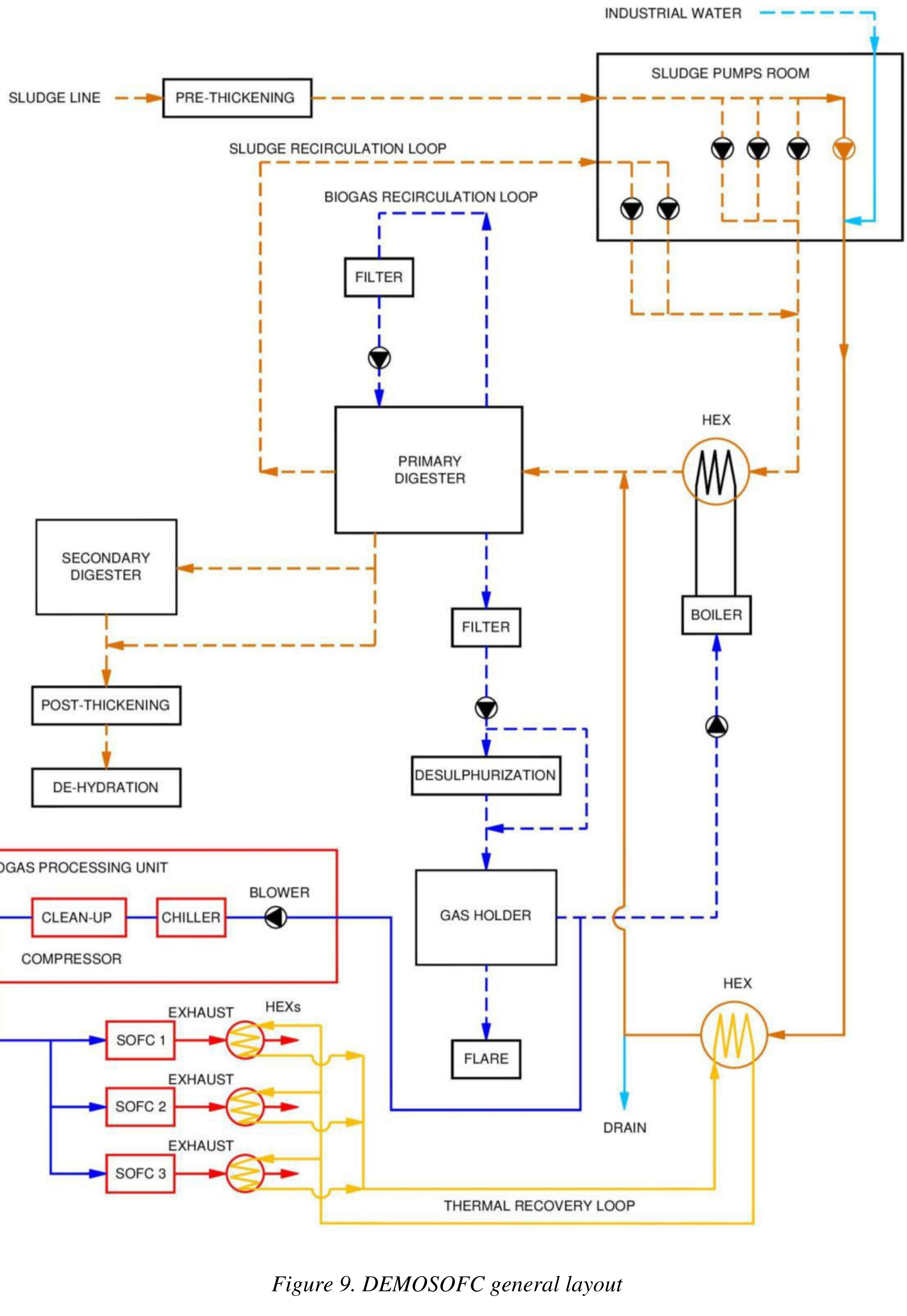


Figure 9. DEMOSOFC general layout

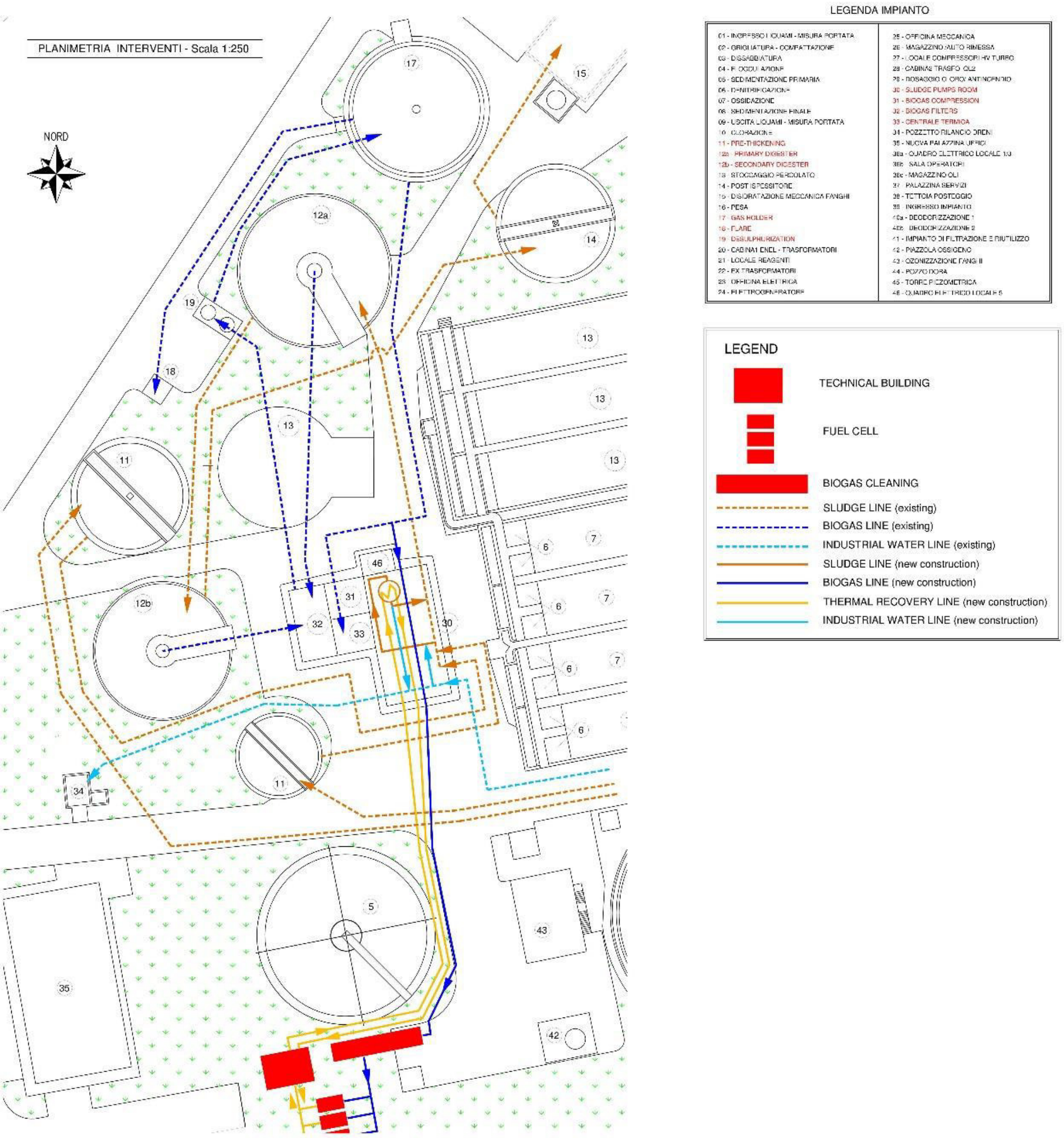


Figure 10. Process flow connections.

3. Description of each unit

In this section a description of each unit is reported.

Starting from the existing site and the biogas production line, a detailed description of the biogas clean-up system, SOFC modules and HRU is presented.

3.1 Waste water treatment plant and Biogas supply system

The general plant description has already been shown on chapter 1 and 2.

Biogas is currently produced from the sludge derived from the water treatment line. Biogas production, as discussed in previous deliverables, is not stable during the year and both hourly and seasonal variations have been detected during 2014 and 2015. The main variation, as shown is Figure 11, is due to the seasonal trend of waste water entering the WWTP. Because of citizens departure from the Turin area during summer months, incoming flow is reduced and consequently biogas is reduced.

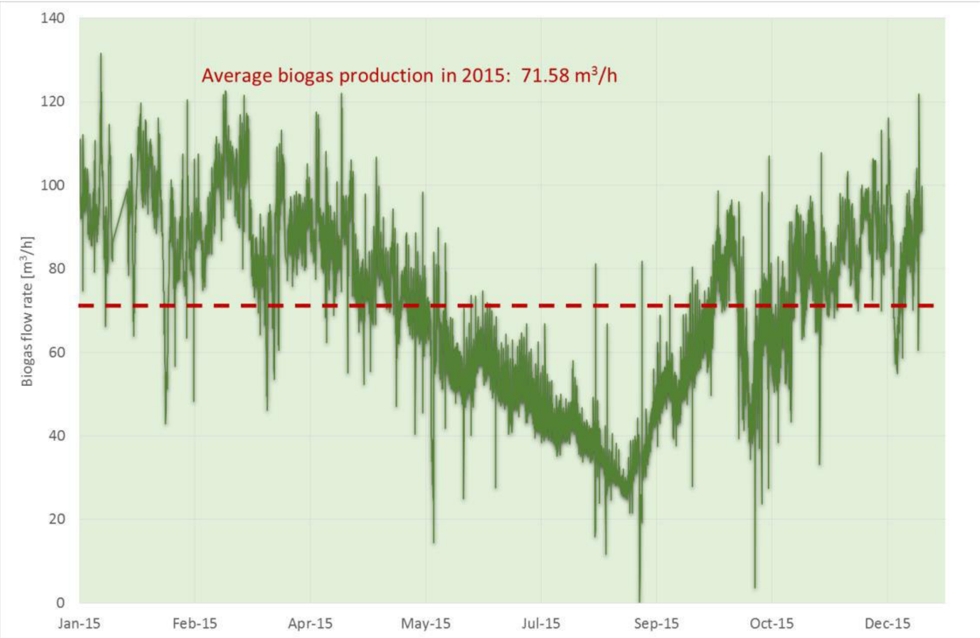


Figure 11. Biogas hourly production during 2015.

Biogas, as described before, is stored is a gas holder. The maximum available storing capacity is 1440 m^3, while the real gas holder volume is 1470 m^3.

Currently, the gas holder is controlled through 4 level sensors (very low, low, high, very high) which are linked to actions on the system (at very low level: stop biogas out from gas holder to boiler, at very high level: flare is activated and biogas burned to atmosphere).

3.2 Biogas processing system

The biogas feeding to the SOFC modules, trace compounds contained in the biogas shall be removed down to ppb(v) levels.

System requirements

A high purity level is required and the technical specifications for the clean-up system are listed below:

- The biogas available from the digester is stored in a gas holder where the gas it stored at a pressure of about 40 mbar.
- The nominal biogas flow rate is 60 Nm3/hr with a variation of +/- 3.3%.
- The gas purity requirement for the SOFC modules is <30 ppb(v) for total sulfur, and <10 ppb(v) for siloxanes compounds. The biogas is also required at a pressure of 4 bar(g).
- The minimum period of continuous operation between each catalyst(s) change should be between 6 and 12 months. A stop of the fuel cell system is expected once per year. So a redundancy of the clean-up vessels (i.e., the installation of spare vessels) depends on the lifetime of the catalyst. Vessels should be changeable without affecting fuel cell operation regardless of the vessel lifetime.

The raw biogas contaminants mainly concern sulfur, chlorine, siloxane and aromatic compounds. The measured concentrations in SMAT Collegno (test campaign during July 2015 – February 2016) are reported in Table 1.

On Table 2, technical data of the gas cleaning system are also reported.

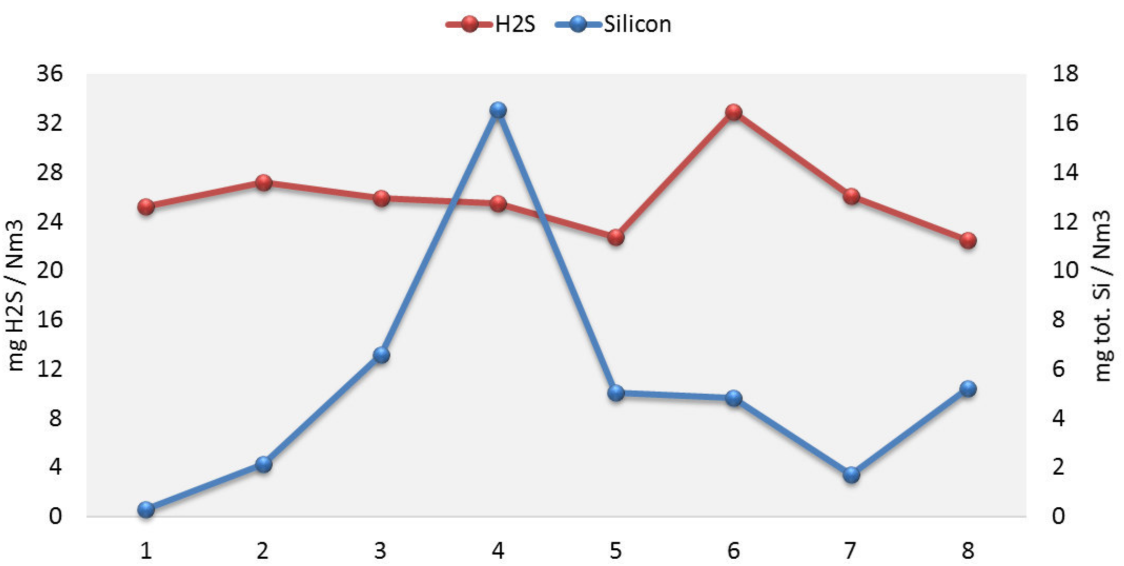


Figure 12. H2S and silicon trend during 2015-2016 gas analysis in SMAT Collegno.

Table 1. Biogas analysis in SMAT Collegno.

Compound	Chemical formula		July 9, 2015	July, 24 2015	Aug 7, 2015	Sep. 16, 2015	Sep. 28, 2015	Oct. 20, 2015	Jan 26, 2015	Feb 12, 2016
Methane	CH_4	[%]	65,5	64,7	63,4	63,8	63,1	64,4	65,9	61,61
Carbon dioxide	CO_2	[%]	32,2	30,39	30,15	31,6	33,3	35,1	33,2	37,98
Oxygen	O_2	[%]	0,33	0,22	0,17	0,11	0,06	0,02	0,02	0,01
Carbon monoxide	CO	[mg/m^3]	2,7	3,1	2,1	1,8	1,2	0,8	0,5	0,3
Hydrogen sulfide	H_2S	[mg/m^3]	25,2	27,2	25,9	25,5	22,7	32,9	26,1	22,5
Sulphur - Mercaptans	-	[mg/m^3]	2,7	2,9	2,4	2,3	2,1	2,6	1,5	1,3
Ammonia	NH_3	[mg/m^3]	0,132	0,112	0,039	0,091	0,052	0,032	0,03	0,01
Total siloxanes			0,82	5,67	17,4	43,8	13,4	12,8	4,55	13,81
(D6) Dodecamethylcyclohexasiloxane	$C_{12}H_{36}O_6Si_6$	[mg/m^3]	0,00	0,17	0,61	1,92	0,95	0,89	0,25	1,26
(D5) Decamethylcyclopentasiloxane	$C_{10}H_{30}O_5Si_5$	[mg/m^3]	0,75	4,08	13,57	33,15	9,80	9,34	3,47	10,41
(D4) Octamethylcyclotetrasiloxane	$C_8H_{24}O_4Si_4$	[mg/m^3]	0,07	1,42	2,87	8,10	2,21	2,25	0,75	2,14
(L3) Octamethyltrisiloxane	$C_8H_{24}O_2Si_3$	[mg/m^3]	0,00	0,00	0,35	0,63	0,44	0,32	0,08	0,00
Si tot (calculated)	-	[mg Si/m^3]	0,31	2,14	6,56	16,52	5,05	4,83	1,72	5,21
Hexane	C_6H_{14}	[mg/m^3]	0,23	0,31	0,29	0,61	0,31	0,36	0,17	0,32
Heptane	C_7H_{16}	[mg/m^3]	0,2	0,26	0,19	0,58	0,12	0,35	0,2	0,16
Toluene	C_7H_8	[mg/m^3]	6,12	5,67	9,41	3,21	8,75	8,76	2,63	2,98
Xylene	C_8H_{10}	[mg/m^3]	0,48	0,77	0,4	0,55	0,17	0,21	0,15	0,14
Limonene	$C_{10}H_{16}$	[mg/m^3]	5,11	4,08	3,81	7,95	8,15	6,76	14,07	13,72
Aliphatic Hydrocarbons	-	[mg/m^3]	118,5	114,2	112,7	116,000	76,7	46,00	48,3	21,4
Aromatic Hydrocarbons	-	[mg/m^3]	3,22	24,5	6,81	6,57	3,98	1,85	2,94	2,24
Alicyclic Hydrocarbons	-	[mg/m^3]	21,4	0,5	22,7	16,3	11,7	9,13	3,17	2,03

Table 2. Cleaning system specifications.

Reference conditions for compression	
Suction pressure (barg)	0.020
Relative humidity (%)	70
Delivery pressure (barg)	4
Operating limits for compressor	
Max. Working pressure (barg)	5
Max. Environment T (°C)	+40
Min. Environment T (°C)	-10
Max. Delivery T (°C)	35
Performance of the compressor	
Biogas flow rate (Nm^3/h)	60
min. and Max. Flow rate for compressor (Nm^3/h)	5-65
Dew point biogas – output (°C)	5-10
Particles output (μm)	<5
Oil concentration in the delivery gas (mg/m^3)	<0.1
min. and Max. Power (kW)	1-7.5
Noisiness level @1mt (dBA)	<75
Clean-up technical data	
Construction material	Stainless steel 304
Chemical reagent for desulfurization	Activated carbon
Chemical reagent for siloxanes removal	Activated carbon
Reactor tank	2 (H_2S) + 4 (Si)
Overall dimensions (mm)	Ø 700 x h 1860
Operating limits for clean-up	
Min. Environment T (°C)	-10
Max. Environment T (°C)	+45
Min. T for gas inlet (°C)	+25
Max. T for gas inlet (°C)	+40
Max. Concentration siloxanes (mg/m^3)	44
Max. Concentration H_2S (mg/m^3)	33
Performance of gas clean-up	
Siloxanes conc. at the outlet (ppb)	<30
H_2S conc. at the outlet (ppb)	<30
Min. Interval of substitution (months)	6

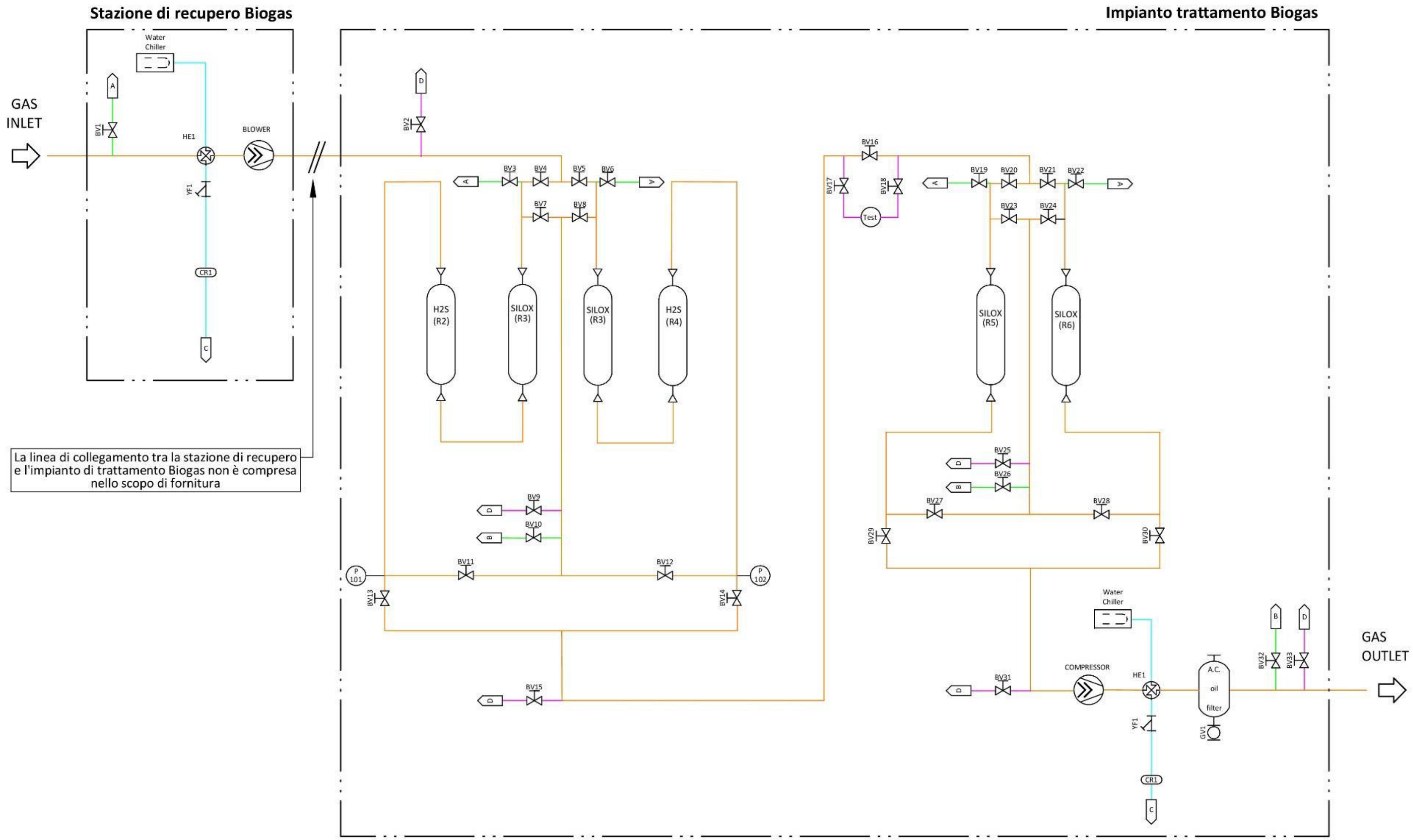


Figure 13. Clean-up system P&ID.

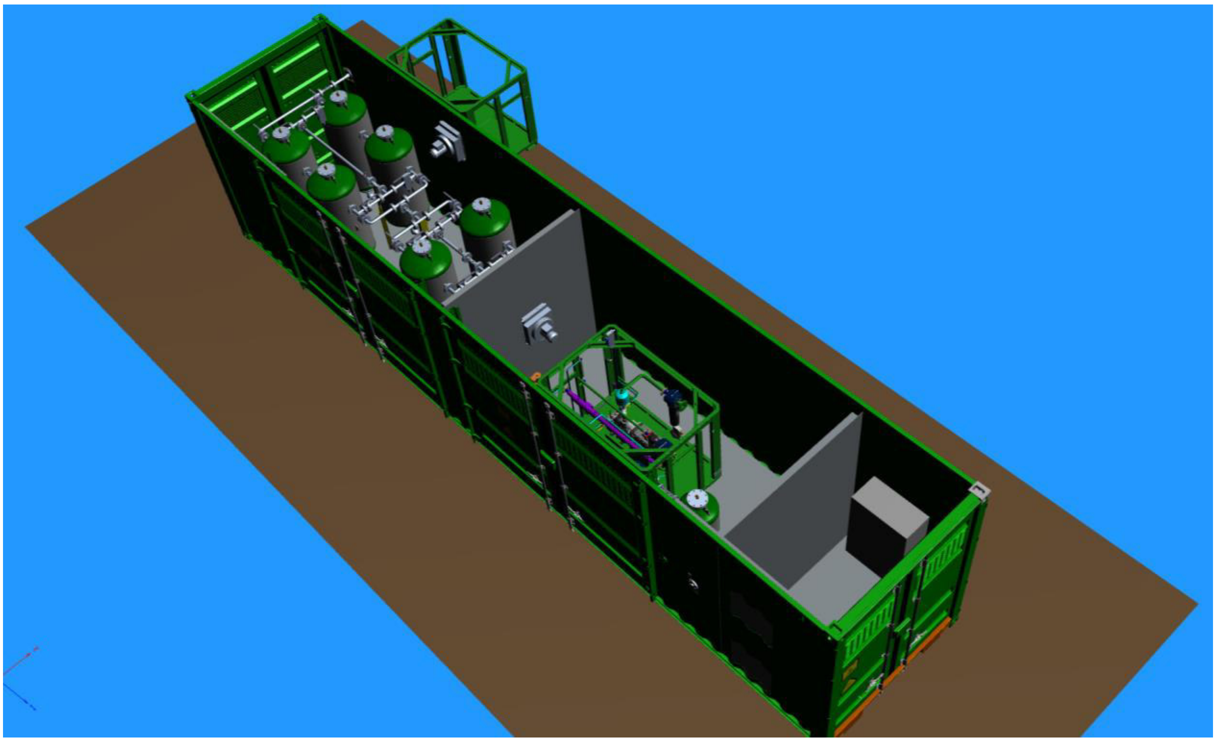


Figure 14. Draft 3D layout of the clean-up unit.

Gas cleaning components and replacement procedure

The gas cleaning system is essentially composed by:

- A gravel filter to rough cut the starting trace compounds concentration.
- A blower to overcome the load losses of the system.
- A series of reactor, where sorbent catalysts are adopted to remove trace compounds down to SOFC requirements. The system is arranged in a lead and lag configuration.
- A compressor to pressurize the pressure of the biogas up to 4 barg. Compressor based on a single rotary group in single-stage oil-injected screw, driven by vector engine (torque control) high-speed, variable flow by means of the speed control with inverter drive (VFD) of the electric motor.
- Two dehumidification system composed by 2 chillers with hermetic scroll compressor and evaporator with finned coil, with a heat exchanger custom-designed and suitable for use with gas. The refrigerant adopted is R410A.
- Multiple internal filtration system to the compressor inlet and outlet for oil removal and final particulate gas <5 microns, with a filtration rate 0.1 mg / m³.
- Optional system with activated carbons to provide a technically oil free gas.

- A protection case able to guarantee the operation of the analytical instrumentation in the range 5/+40 °C.
- LV electrical panel to power the compressor, chiller and auxiliary with the control and supervision system based on touch screen panel repositioned via Ethernet, located inside the electrical room classified as safe area.

For lead-lag configuration two columns of the same size are used. One column is placed in a “lead” position, the other one serves as a “lag” or “guard” column. Sample breakthrough curve for two columns placed in a lead-lag is shown in figure 1. The system continues operation until the effluent from the lag column reaches the target concentration. This concentration is detected through a gas cromatograph installed on site, adopted to control not only the state of sorbent to remove mainly H_2S, but also to consider the state of the reactor in which siloxanes are removed. Then, the saturated column R2 (left) is taken out of operation and column R1 (right) is connected as a new “lead”. The replaced, fresh column 2 is installed in a “lag” position, providing polishing for the effluent from column 1.

This lead and lag configuration can be viewed as a safety net to account for variations in operating conditions (such as temperature and the inlet concentration of the contaminant) with no plant stoppage.

The configuration selected is reported in the following figures.

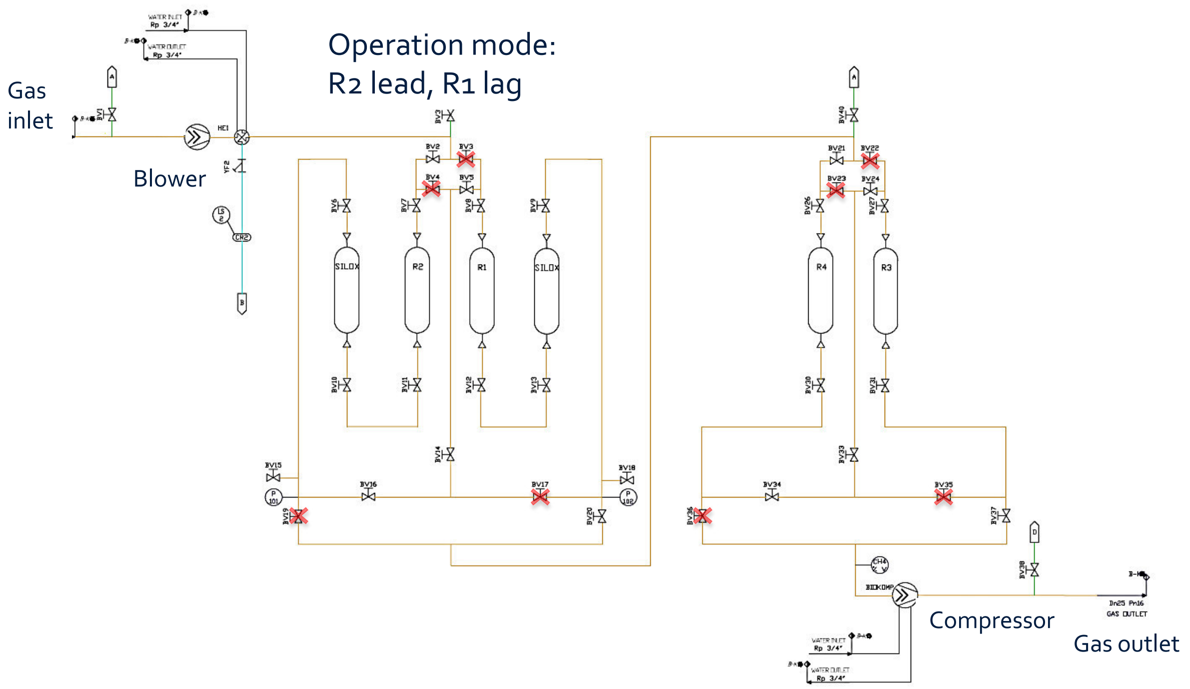


Figure 15. Operation mode for R2 lead and R1 lag configuration.

The configuration reported in Figure 15 considers R2 and R4 as “lead” while R1and R3 is the “lag” reactor, the manual valves that should be closed are: BV3, BV4, BV19, BV17 and BV22, BV23, BV36 and BV35.

In order to replace the spent sorbent material contained in R2 and siloxanes reactors the procedure needs the following steps using manual valves:

- Open BV3,
- Close BV5, see fig.2, fuel stops flowing through R2.
- Then close BV2,
- Before disconnecting pipes to R2 and Silox., N2 flush can be used to prevent release of flammable gas to the room,
- R2 and Silox. now are disconnected from fuel feed and the spent sorbent material could be replaced,
- After connecting reactors with new adsorbents, N2 flush can be used to remove air from the reactors and pipes.
- After connecting reactors and after flushing N2, open BV2 to flush new sorbent material with biogas. Biogas flush of changed reactors is needed to prevent discontinuities in fuel composition. The amount of ventilation needed has to be estimated considering when this operation has to be stopped, using the analyzer measurements can be appropriate,
- Close the vent and BV2, now R2 is filled with fuel gas, but biogas is not flowing through the reactors,
- Close BV16, then open BV19. Biogas still flows through R1 only. There is no need to operate the valves BV16 and BV19 simultaneously,
- Open BV17. Biogas still flows through R1 only. Keeping BV4 closed at this point prevents dirty gas from entering pipe section between BV4, BV5, BV16 and BV17,
- Open BV4, then close BV20. R2 now is connected as lag reactor. There is no need to simultaneously operate BV4 and BV20. Even after opening BV4, the flow goes through R1 only since that is the “easier route”.

The procedure reported above needs to be replicated for the scavenger, reactor R3 and R4.

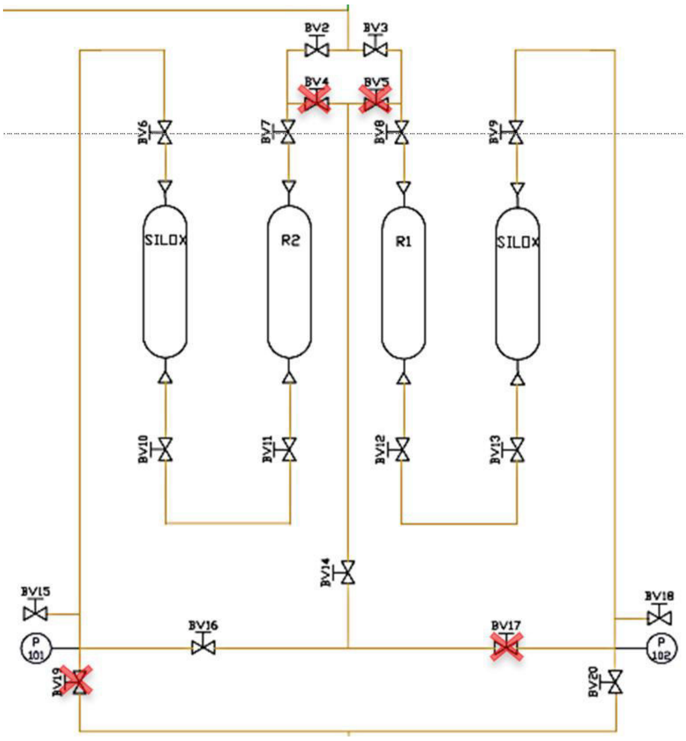


Figure 16. Operation mode for replacing R2 and Silox. – step 1,2

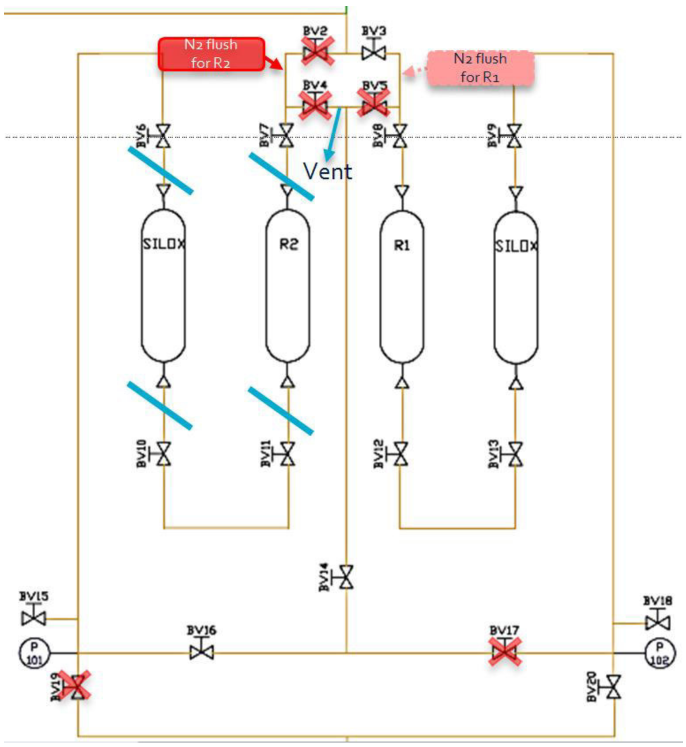


Figure 17. Operation mode for replacing R2 and Silox. – step 3,6

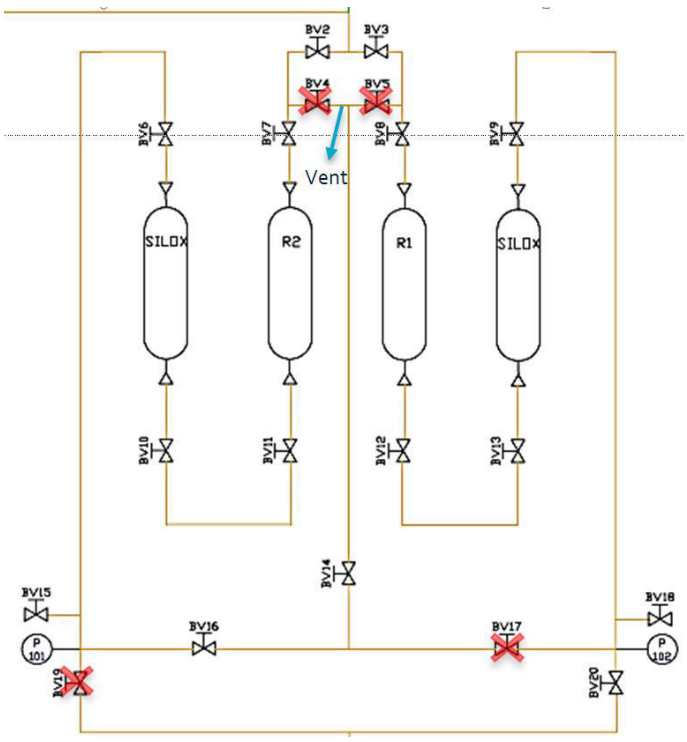


Figure 18. Operation mode for replacing R2 and Silox. – step 7

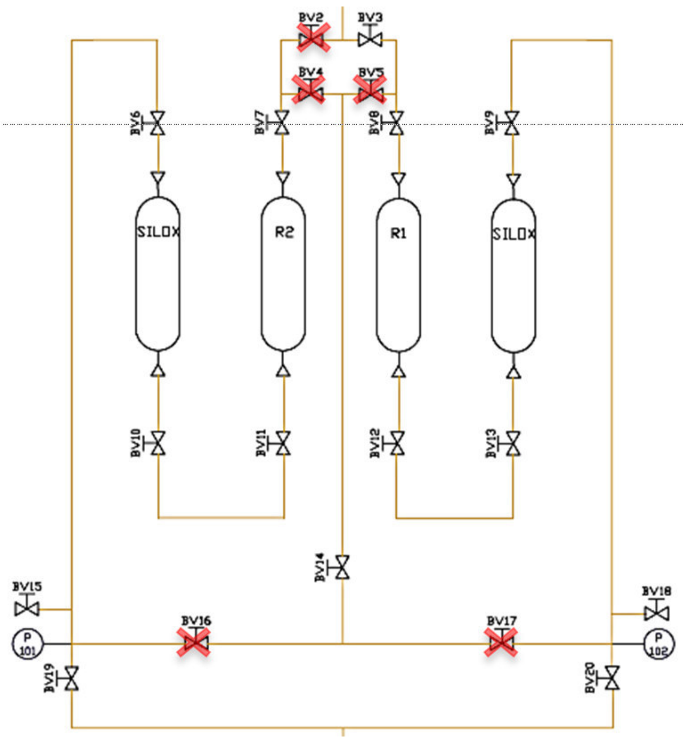


Figure 19. Operation mode for replacing R2 and Silox. – step 9

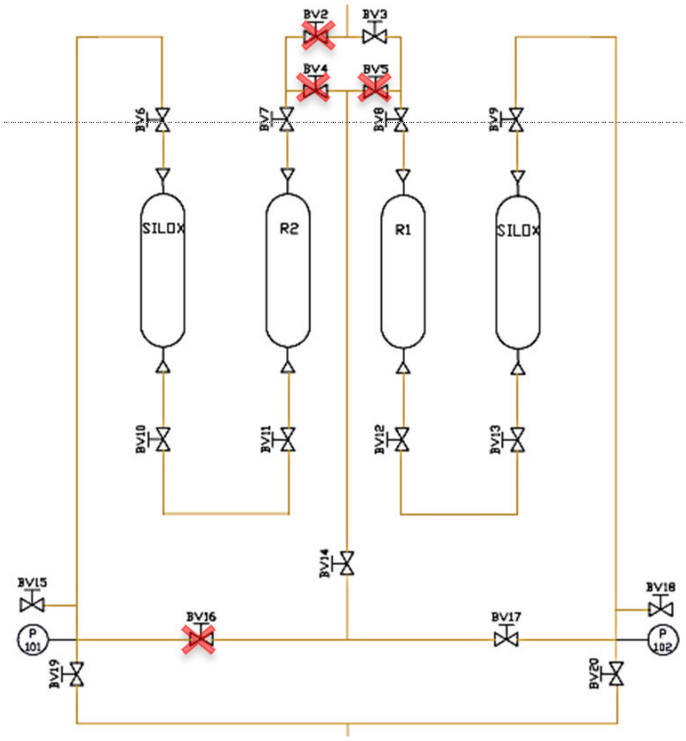


Figure 20. Operation mode for replacing R2 and Silox. – step 10

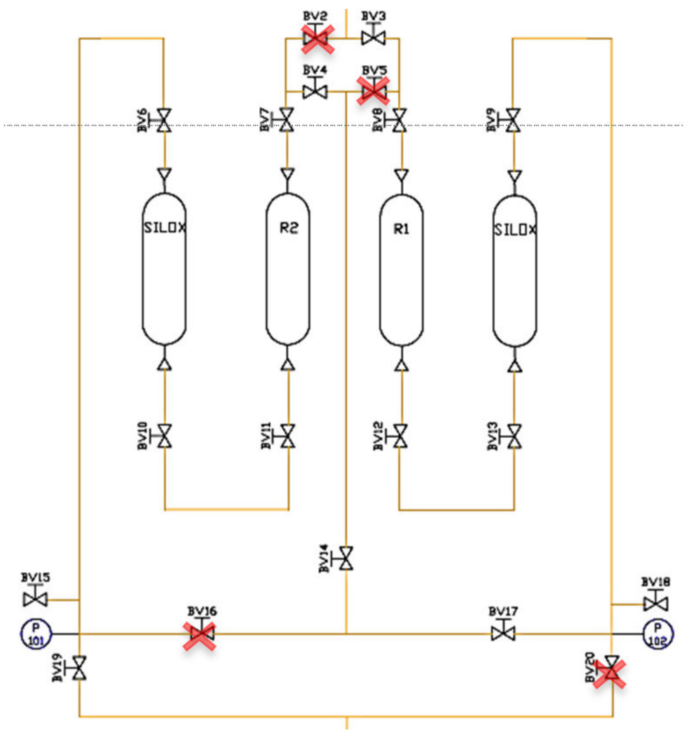


Figure 21. Operation mode for replacing R2 and Silox. – step 11

Sampling points and monitoring system for trace compounds

The analyzer system is composed by a Qualvista online monitoring based on NDIR method, in order to monitor constantly mainly H_2S, other sulfur compounds and siloxanes to understand when the sorbent material should be replaced. According to Figure 22 ,SAMPLE PORT #1 determines when a catalyst change on the lead reactor is required. SAMPLE PORT #2 is monitored just as additional safety check during normal operation. During the catalyst replacement in one of reactors, SAMPLE PORT #2 is also necessary to maintain knowledge of biogas quality at the outlet of the clean-up section.

SAMPLE PORTS #1 and #2 should therefore measure ultra-low levels of both S and Siloxanes. SAMPLE PORT #3 serves instead to measure the as-received biogas composition. In this section of the plant, biogas is only slightly pressurized to overcome pressure drops in the adsorbtion beds. Pressurization up to 4 bar(g) is carried out after the clean-up section by a compressor.

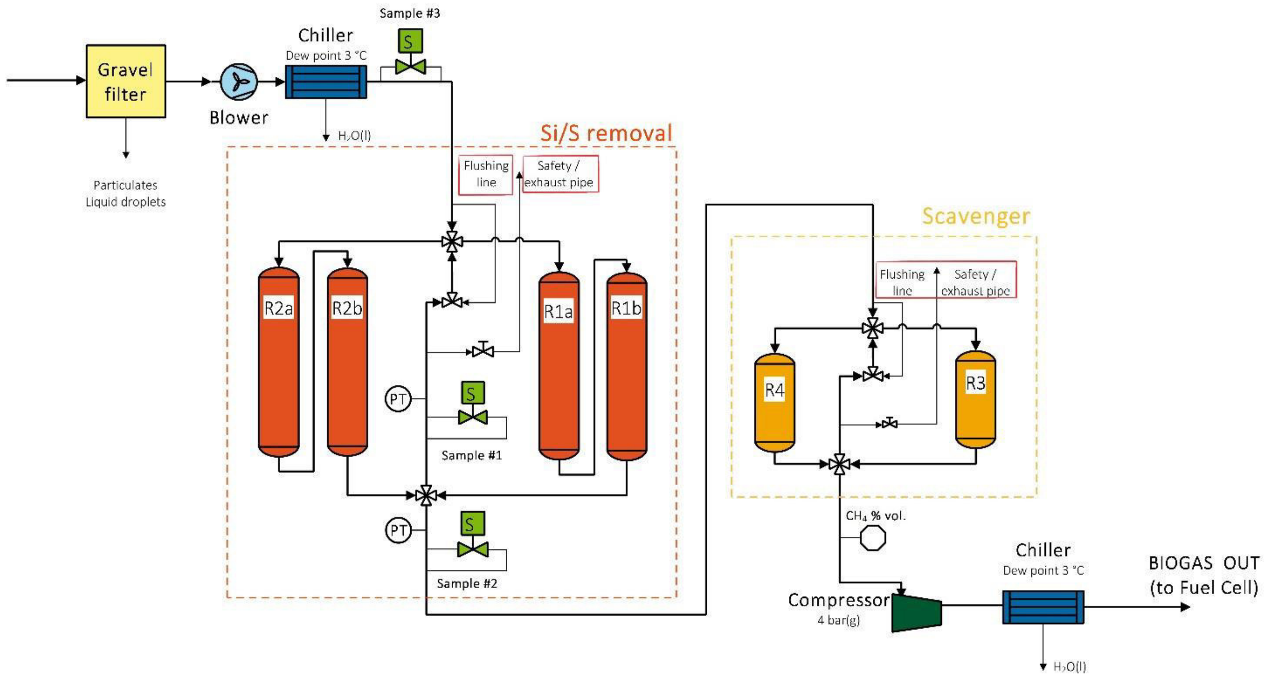


Figure 22. Sample ports (#1 and #2) for gas analysis equipment.

Gas analysis equipment

Key characteristics of the gas analysis equipment:

- measurements of siloxanes: a minimum detectability of 0.1 – 0.5 mg tot. Si / Nm^3 is requested for total silicon. Also a rough separation of L (linear) and D (cyclic) compounds is requested for siloxanes,
- measurements of H_2S: a detectability range between 0.05 – 2 mg tot. S / Nm3 is requested for total sulfur,

- CH_4 monitoring (range 0-100% vol. or 40-100% vol.) is required to control the biogas quality and heating value.
- CO_2 (range 0-100% vol.) and O_2 (range 0-10% vol.) monitoring is mandatory. The measuring device shall use the same gas sampling port used for CH_4 monitoring,
- online, fully-automatic and real-time measurment of the above listed compounds,
- fully-automated sampling and analysis of a multiple number of measuring points (in our specific case 3 measuring points are required),
- condensate trap including level guard, automatic drain and purification (N_2); especially, those measuring devices devoted to H_2S and siloxanes detection shall include a system for the automatic purification and/or purging (e.g., with N_2 or other inert gas) of the involved measuring device after each sampling & measurement event. This is required in order to avoid "memory" effects. In fact, the system is used to measure alternativaly either 'high' or 'ultra-low' concentrations of the same trace contaminants (Sample Port #3 shall measure high concentrations, while Sample Ports #1 and #2 shall measure ultra-low concentrations). Therefore, it is of utmost importance to purge the system after each measurement in order to avoid unreliable results.

The gas analysis equipment should be able to monitor online the three sampling points. A minimum of 4 measurements per compound per hour is requested in the case of both H2S and total silicon amounts in biogas (i.e., a new detection point must be taken at least every 15 minutes). The system should be able thus to provide at least 96 measurements per day for both H2S and total silicon. The intervals and rotation of the measurements (i.e. the sequence of sampling among the three Sample Ports) must be modifiable/changeable. As far as it concerns CH4, CO2 and O2, the monitoring frequency should be at least 6 samples per hour (note that only 1 sampling port is used in this case, e.g., Sample Port #2).

3.3 SOFC section

Convion C50 is a modular solid oxide fuel cell power generator with a nominal power output of 58kWe (AC Net). The product can be configured for operating with different fuel gas compositions and has a readiness for exhaust heat recovery. By its modular architecture, multiple C50 units can be installed in parallel to achieve higher power outputs. Nevertheless, each module is a separate generator, able to operate autonomously. C50 is designed to be installed parallel to power grid but is capable of island mode, thus securing critical power loads within a micro grid. C50 is intended for continuous operation in a base load type generating mode. Table 3 below specifies ambient conditions.

Table 3. Generic operating conditions.

Ambient conditions	
Seismic vibration	IBC 2003: Site class D
Rain	IP54
Temperature [°C]	-20 – +45
Altitude [m]	0 – 1000
Ambient humidity RH, %	0 – 99
Installation	Indoor / Outdoor

A standard C50 fuel cell unit consists of a stack module as well as process, automation and power conversion equipment for facilitating power generation from the unit. At the C50 module interface, pre-cleaned and pressurized fuel and clean, non-condensing pressurized air is required. Process air is taken in by C50 at ambient pressure. Inside of C50 system enclosure there is an interface for a heat recovery. The heat-exchanger will be place inside the unit.

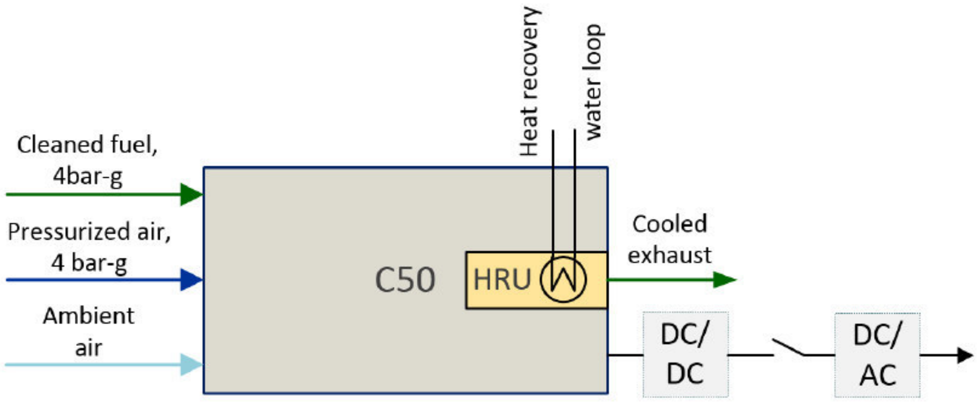


Figure 23. Schematic of C50 interfaces.

Output of a single C50 module is summarized below in Table 4. Total efficiency depends on heat recovery effectiveness and temperature.

Table 4. Summary of typical C50 system output.

Energy output	
Fuel	NG 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 of exhaust flow [J/kg, K]	1072
Allowable back pressure [mbar]	25
CHP capability	Optional
Overall efficiency (CHP @ 60 °C), %	> 80
Noise level (dB(A) at 1 m)	< 70
Island mode operation	Optional

Power connection

C50 unit can be connected to the power grid acc. to IEC61800-3 standard and local grid codes. The market specific requirements for the connection are defined in the local grid codes which can be adapted according to customer need. Electrical connection is characterized in table below.

Table 5. Power connection data.

Power connection	
Electrical connection, capability	3x380-500V AC 50/60 Hz
Grid current, apparent [A]	105
EMC emission level	2nd environment – Power drive system of category C3 – I >100A, (IEC 61800-3)
Electrical connection, [Vac]	400
Grid current, active [A]	83.7
Grid current, reactive [A]	63.4
Apparent power [kVA]	72.7
Reactive power [kVar]	43.9
Surge protective device	1.5 kW 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)
Communication	Industrial Ethernet, Conformance class B

C50 product is designed for operation either with natural gas or bio gas. Pressurized fuel is supplied to the C50 power unit after fuel cleaning, where harmful impurities such as sulphur compounds are removed. Process module air intake is handled by a blower inside of the cabinet and vents for process and ventilation air are equipped with appropriate filters. Quality requirements for cleaned fuel and air are presented in Table 6. Air quality affects filter exchange intervals and therefore ambient air with high level of particle pollution will lead to shortened filter exchange intervals.

Table 6. Summary of fuel and air quality requirements.

Unit inputs requirement	
FUEL	
Pressure [barg]	4 +/- 0.2
NG/ Biogas composition	
CH4 [%mol]	55-100
C2H6 [%mol]	0-7
C3H8 [%mol]	0-4
C4H10 [%mol]	0-1
CO2 [%mol]	0-45
O2 [%mol]	0-1
N2 [%mol]	0-45
LHV [J/kmol] @ 25 °C	441-850
Temperature	-10 / +40 °C
Fuel impurities	
Max sulphur content at system inlet	< 30ppb i.e. <0.04 mg(S)/m3 of total sulphur (originating from H2S, COS, THT, DMS etc.)
Siloxanes [ppb]	< 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. Cl2, HCl, halogenated hydrocarbons)
Allowed level of humidity	Non-condensing @ ambient temperature and fuel supply pressure
AIR	
Air quality	Ambient air* **Filtering and filter exchange intervals are based on upper assessment threshold for particulate matter (PM10 /PM2,5): annual average of 14/ 10 µg/m3 (as defined in EU directive SEC(2005) 1133); filtration requirements in harsher environments are to be determined individually by Convion. When typical humidity level exceeds 2 mol-% H2O in air for more than 40% of annual operating hours,*

	applicability must be confirmed by Convion.
Temperature [°C]	-20 / +40
PRESSURIZED AIR	
Pressure [bar-g]	≥4 bar-g
Temperature	-10 / +40 °C
Allowed level of humidity	Non-condensing @ ambient temperature and pressurized air supply pressure
Oil (i.e. compressor hydrocarbon lubricant) concentration	<0.01 mg/m3
Other contaminants, e.g. sulphur (S), silicon (Si)	See Fuel Impurities
CONSUMABLES	
	Formier5 (95 % N2, 5 % H2), 1pcs 20 l/200bar cylinder placed inside C50 covers; alternatively an external supply.

Fuel gas supply

Fuel gas shall be cleaned and pressurized upstream of C50 fuel cell unit. Table 6 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.

Heat recovery connection

The C50 product can be equipped with an optional heat recovery units which installed inside the C50 power unit. The properties of the standard heat recovery connection are presented in table below.

Table 7. Heat recovery connection.

HRU Liquid coolant flow conditions	
Min operating temperature (°C)	10
Max operating temperature (°C)	110
Min operating pressure (barg)	2.5
Max operating pressure (barg)	6
Min flow rate * (m3/h) **(pressure drop) (mbar)** **[Heat exchange] (kW)**	0.6 – 0.72 (40) – (55) [28]
Max flow rate * (m3/h) **(pressure drop) (mbar)**	2.4 (540)
** based on 50/50 vol-% water ethylene glycol mixture*	

HRU Liquid coolant quality	
General requirement	colourless, clear and free on undissolved substances
pH value (at 25 °C)	9.0 - 10.5
Conductivity (at 25 °C) (microS/cm)	< 250
Oxygen (O2) (mg/l)	< 0.05
Chloride (Cl) (mg/l)	< 20
Alkaline earths (total hardness) mmol/l (°dH)	< 0.0 (<0.1)
Phosphate (PO4) (mg/l)	5 - 10
Na3PO4 must be used for basic alkalinisation. Dosage of sodium hydroxide solution (NaOH) is permitted with written approval only *Make-up water: low salt desalinated water* *Note: above requirements do not apply if drinking water is heated with circulating water*	

Exhaust emissions

Convion C50 product is a power generator which utilizes fuel energy efficiently without generating practically any local emissions such as SOx, NOx, VOC or particulate emissions. Sulphur compounds are removed from fuel feed stock upstream of the fuel cell unit and power conversion occurs in temperatures which do not promote formation of nitrous oxides or particulates. Table 8 below summarizes exhaust emissions from a C50 fuel cell unit. CO2 emissions are based on operation with natural gas. When the unit is operated with renewable biogas, no CO2 emissions with fossil origin are generated.

Table 8. Summary of emissions levels of a C50 unit.

Emissions	
Nitrogen oxides, NOx [ppm]	below detection limit of 2, no preconditions for formation
Sulphur dioxide, SO2 [mg/kWhe]	negligible, sulphur removed from fuel before use
Carbon monoxide, CO [ppm]	< 20
Carbon dioxide, CO2 [kg/MWhe] @ nominal load, BoL	374
VOC [mg/Kwhe]	0, below detection limit
Noise level at rated power [dBa @ 1m]	≤70

Modes of operation

C50 SOFC system has five different operating modes – off mode, heating and loading mode, hot standby mode, cooling mode and failure mode. These modes are described in Figure 24.

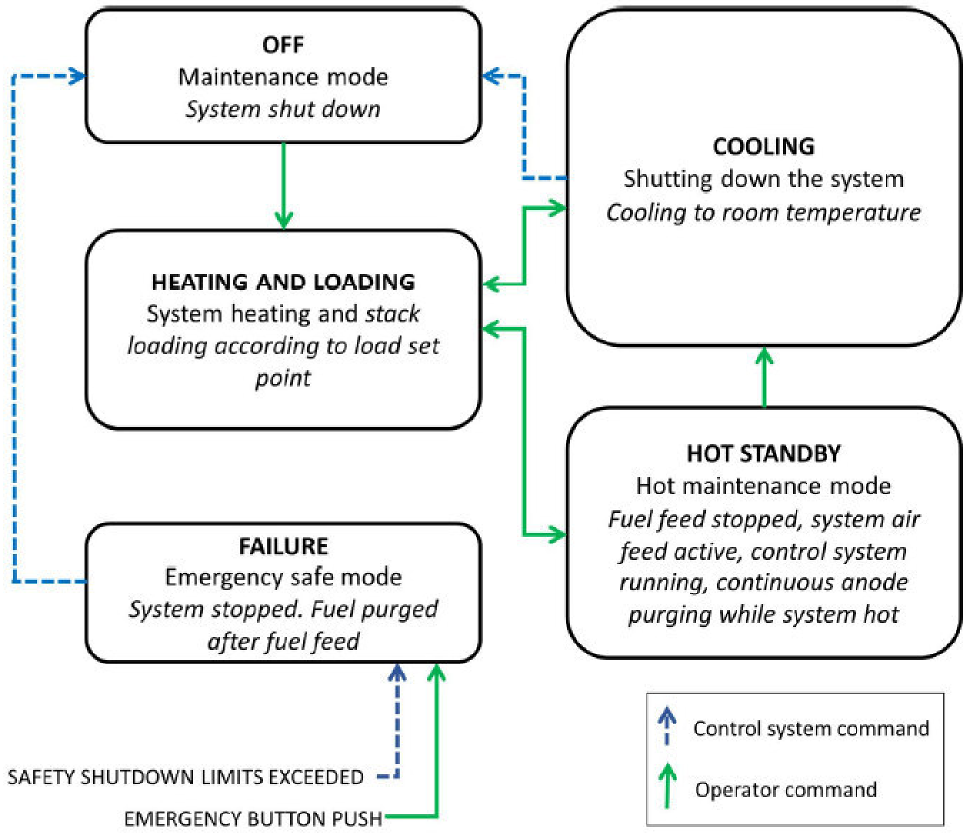


Figure 24. C50 system modes of operation and transitions between modes.

When the system operates in a given state, it maintains that state according to internal control constraints and operating set-point. Figure 24 illustrates mode transitions and signals required to trigger mode transients.

➢ <u>Start-up</u>

Start-up is initiated by an operator command to instigate a mode transition from off mode to heating and loading mode. System heat-up is carried out by circulating electrically heated air while heating up the fuel cell stacks and system. At a pre-determined temperature minimum fuel flow needed for maintaining necessary thermal and chemical conditions in the system is initiated. The heating continues until the fuel cell stacks reach approximately 700 °C. Then electrical loading of the stacks is ramped up while increasing fuel feed. Figure 25 illustrates negative efficiency of the system at start-up mode, when electrical heating is used for heating up the system. Heat-up of a cold system to full load takes over 24 hours.

Whenever fuel is supplied to the system the cathode air feed is maintained at a level causing dilution to below LEL at the afterburner and thus, effectively avoiding a possibility of accumulation of explosive gas mixture anywhere in the system.

➢ <u>Normal operation</u>

In normal operation the system is kept at as steady conditions as possible, regulating the air feed according to measured stack temperatures. In normal operation, loading of the system is based on operator set point.

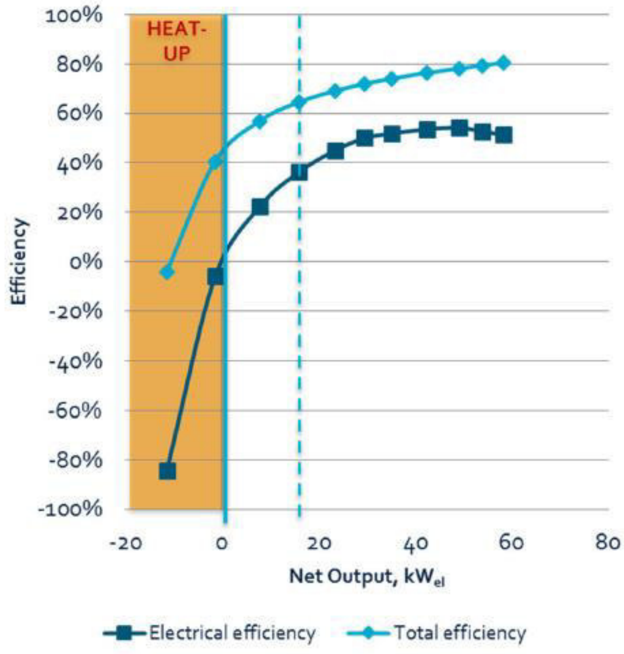


Figure 25. Efficiency of C50 at partial load, including heat-up stage when efficiency is negative due to electrical heating.

By nature, a high temperature fuel cell system is best suited for steady loading and has a limited load following capability due to thermal inertial of the stacks. Maximum stack current ramp up/down rate is 4% of total range per minute. Recommended current modulation range 100%-30% is illustrated in Figure 25.

➢ <u>Modulated normal operation</u>

By nature, a high temperature fuel cell system is best suited for steady loading and has a limited load following capability due to thermal inertial of the stacks. Maximum stack current ramp up/down rate is 4% of total range per minute. Recommended current modulation range 100%-30% is illustrated in Figure 25.

➢ <u>Temporary hot stand-by</u>

Due to long heat-up times and a preference to avoid thermos-cycling of the system, an operator may choose to take the system to a hot stand-by mode for example to facilitate short term maintenance actions that require disconnection of fuel flow. In hot-stand by, system is not actively cooled but instead, only a protective atmosphere is maintained in the stacks. During a short term hot-stand by, system cools down passively but does not experience a full thermocycler and can be brought back to full power relatively quickly.

➢ <u>Shut-down</u>

In normal shutdown, the start-up procedure is essentially reversed. This is triggered by an operator command to instigate mode transition from heating and loading mode to cooling mode and eventually a control system command to bring the system to off mode. In this sequence, stack current is first ramped down to zero. Then fuel supply does not stop when net power generation reaches zero but is needed for maintaining necessary thermal and chemical conditions in the system until system cool down has reached a point when fuel supply can be closed and the fuel system is flushed with air to remove any carbonaceous species that form harmful compounds by chemical reactions. Thereafter cathode air cooling continues until stacks have cooled down to below 100 °C.

➢ <u>Emergency Shutdown</u>

In case of a gas alarm or other failure preventing normal operation or shutdown, the emergency shutdown sequence is triggered. In this case cathode air feed is discontinued, cathode air feed valves closed and the fuel system is flushed for a predefined time with nitrogen. The system then cools down passively without any feed.

In case of a gas alarm all non-ex equipment in the process module is de-energized and the SOFC stacks in the stack module are disconnected from the DC/DC converters. Ventilation of the process module continues approximately 12 hours by means of an explosion safe suction blower with power backup.

Table 9. SOFC module procedures.

<table>
<tr><th colspan="5">1 module C50</th></tr>
<tr><th>Procedure - Time</th><th>Fuel [kg/h]</th><th>Compressed Air [kg/h]</th><th>NH-mix (95% N2, 5% H2) [kg/h]</th><th>Power [kW]</th></tr>
<tr><td colspan="5">START-UP</td></tr>
<tr><td>5-8 h</td><td>0</td><td>≥ 9</td><td>0</td><td rowspan="2">40 all time</td></tr>
<tr><td>10-16 h</td><td>3</td><td>≥ 9</td><td>0</td></tr>
<tr><td colspan="5">SHUT-DOWN</td></tr>
<tr><td>10-16 h</td><td>3</td><td>≥ 9</td><td>0</td><td rowspan="2">5 all time</td></tr>
<tr><td>24 h</td><td>0</td><td>≥ 9</td><td>0</td></tr>
<tr><td colspan="5">Emergency SHUT-DOWN</td></tr>
<tr><td>Immediately de-powered, ~48h to cool down</td><td>0</td><td>0</td><td>3</td><td>0</td></tr>
<tr><td colspan="5">HOT STAND-BY</td></tr>
<tr><td></td><td>0</td><td>0</td><td>3</td><td>2</td></tr>
</table>

Safety design

The first priority of the system safety design is to eliminate explosion risk. 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.

Application interfaces

- <u>Installation site and foundations</u>

Figure 26 shows an exemplary installation of three parallel C50 units together with necessary maintenance areas. Weight of a single C50 module is 6000kg and the installation site must be designed to withstand a maximum point load of 1000kg under a single foot of the unit. For installation of the units, access to the site with a truck or a forklift with lifting capacity of minimum 6 ton is needed. In the example of Figure 26, fuel feed-in pipes and cables are brought to the units in a 150 mm wide trench at the cold end of the units. An alternative to a trench is to place the units on an elevated floor for allowing for sufficient clearance for pipe and cable connections.

Additional to the C50 fuel cell modules is a power electronics (PE) cabinet (1200 x 2300x 600 mm). The PE cabinets are recommended to be installed indoors with a maximum distance of 30 m from the power unit(s).

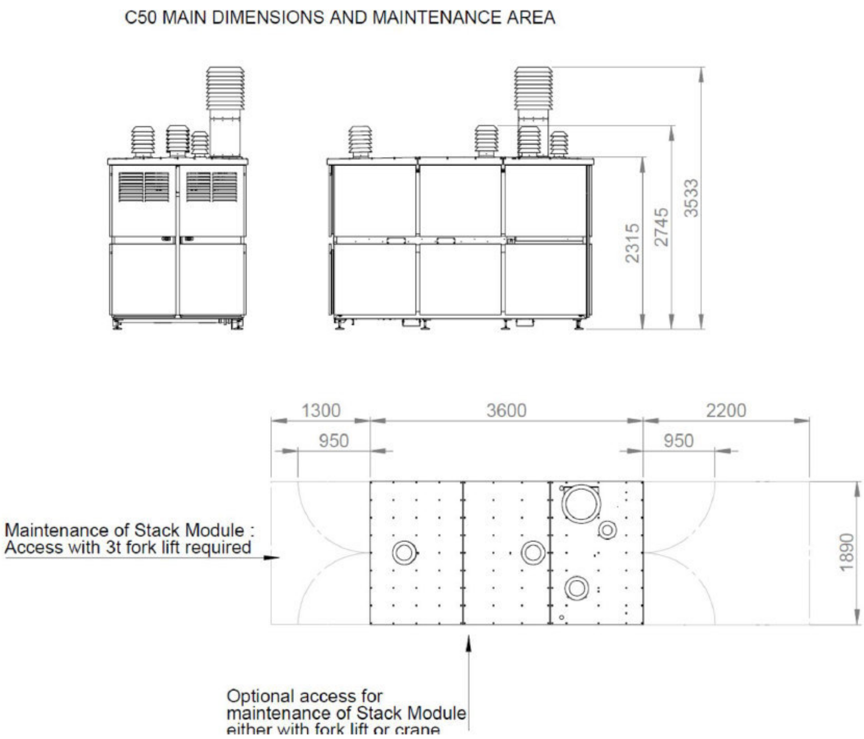


Figure 26. Dimensions of a C50 installation.

➢ <u>Grid interface</u>

C50 fuel cell systems should be integrated to grid in accordance with local grid codes. Frequency and voltage protection device may connect and disconnect contactors of C50 fuel cell systems as the local grid code requires.

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 27 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.

C50 fuel cell systems connects to grid with two 3-phase grid connecting contactors in series. Sizing of grid connecting contactors is installation specific.

Grid connecting contactors connects to 3-phase bus bars at the local grid side, i.e. SOFC units' side of contactors. Bus bars are installation specific point of common coupling for devices at the local grid. A circuit breaker as a cable protector with 125A continuous current rating and appropriate short-circuit interruption capability from bus bars to each SOFC units should be provided. MCCMK 3x35/16 cable should be used in between the circuit breaker and connections of a SOFC unit.

3-phase 400V / 50Hz IT-grid is used for AC auxiliary devices of SOFC units, and may be used for securing electricity supply of other devices during power outage. Connections of AC auxiliary devices and secured loads to bus bars, i.e. point of common coupling, are installation specific.

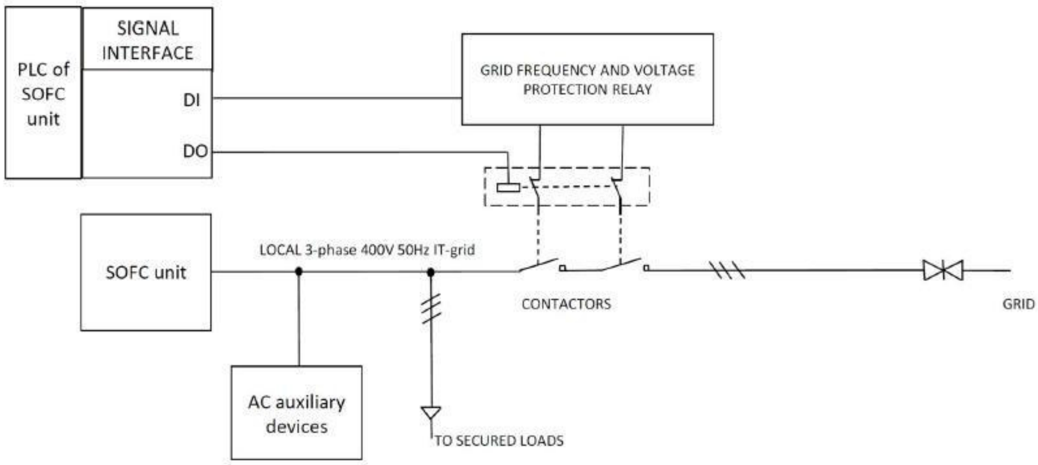


Figure 27. One-line diagram of grid interface of Convion C50.

- Automation and control

Automation interface between plant and fuel cell units can be configured according to needs of facilitating safety related functions, power request and auxiliary device operation and to facilitate heat recovery.

Additional state signals can be made available for optimization of local energy system. Grid voltage and frequency are available for the operator of electric grid.

It is required that AC auxiliary devices of C50 fuel cell systems have power loss ride through or restart at fault capability. This requirement is due a short power loss at the local 400Vac grid in change from the grid parallel to island mode. It is recommended that use of hysteresis control in AC auxiliary devices is avoided.

- Heat recovery

Convion C50 is CHP ready, i.e. heat of its hot exhaust flow can be recovered by means of a heat exchanger for a maximum total efficiency. For the most compact arrangement Convion can supply the C50 unit equipped with heat exchanger fitted inside C50 enclosure. Alternatively, heat exchanger may be placed outside of the C50 enclosure. Exhaust gas pipe size at connection points is DN150. Exemplary counter flow arrangement of the heat exchanger is illustrated in Figure 28.

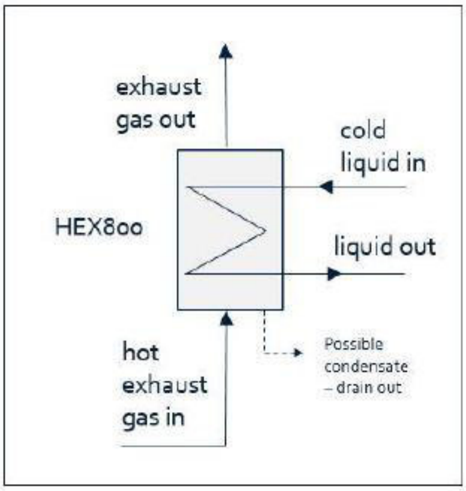


Figure 28. Flow arrangement of a heat recovery heat exchanger.

Maximum allowable pressure drop on the exhaust gas side incurred by exhaust gas flowing through a heat exchanger is 25 mbar. While exhaust gas temperature in all normal full or partial load operating points is below 250°C, an instantaneous peak temperature of 500°C during a rare event of emergency shutdown may be experienced, although duration of peak temperature is short, order of 120s, and during that period exhaust gas flow drops to a low level of about 20kg/h.

Aside of the pressure drop caused by the heat exchanger, operation of heat recovery shall not affect fuel cell system operation in any way. Control and mitigation of possible abnormal operation of the heat recovery system shall be taken care of by an external heat recovery system and its controls. It is not advisable to combine exhaust flows of more than one unit for a common heat recovery instead of using individual heat exchangers. Should an integrator wish to do so please consult Convion during the planning phase.

Compliance

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

- Machinery Directive 2006/42/EC ,
- Low Voltage Directive 2014/35/EU,
- 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

- Metallic Industrial piping (parts 1 to 5) SFS-EN 14380

Note that:

- C50 consumes pressurized fuel and air. 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 C50.
- C50 is not supposed to operate in an ATEX environment and therefore do not comply with ATEX directive. However, explosion hazard in C50 will be assessed to comply with the requirement of Machine Directive and hazardous areas will be classified according to the zone definition specified in the standard IEC 60079-10-1.

C50 conformity assessment procedure will demonstrate compliance of C50 with the technical requirements of the Directives and on passing the relevant type tests specified in the Fuel Cell standards. This applied assessment called “Internal Production control” in the frame of CE marking principle will be done by Convion; the type tests will be realized by a person independent from Convion and all the test results will be collected in a test campaign document.

The test campaign for the EMC compliance will be 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, and the C50 CE marking will only be possible at the end of the 3rd test campaign passed. Pre-compliance EMI tests have been run on a prototype but, final assessment has to be carried out due to hardware updates on C50.

The C50 product will be provided with following documentation

- Operational manual
- Service manual
- Installation manual

The technical C50 commercial datasheet is finally shown on Figure 29.

Performance	Targets
Net power output	58kW (3x400-440V AC 50/60Hz)
Energy efficiency (LHV)	
Electrical (net , AC)	> 53 %
Total (exhaust 40°C)	> 80 %
Heat recover	
Exhaust gas flow	650 kg/h
Exhaust gas temperature	222 °C
Emissions	
NOx	< 2 ppm
Particulates(PM10)	< 0.09 mg/kWh
CO_2 (NG, nominal load)	354 kg/MWh
CO_2 (with heat recovery)	234 kg/MWh
Fuels	Natural gas, City gas, Biogas
Dimensions (L x W x H)	
power unit	3,5 x 1,9 x 2,3 m
aux. equipment	2,4 x 0,6 x 2,2 m
Noise level	< 70 dB(A) at 1 m
Installation	Indoor / outdoor
Temperature	-20 – +40°C

Figure 29. Convion SOFC modules datasheet.

3.4 Thermal recovery system from the SOFC section

The thermal recovery loop P&ID is shown on Figure 31. The technical drawing is also available in Appendix E.

SOFC modules are represented on the left, fed by biogas (blue line) or auxiliary gas (NH-mix, blue line). Inside the SOFC modules, the first heat-exchanger (gas-liquid) will be placed. Heat released for the hot exhaust gas stream (green line) is transferred to a water+glycol loop (brown lines).

The three water+glycol streams, one per each module, are then connected together and sent to the second heat-exchanger (liquid-liquid), fed on the other side by the incoming sludges to the digester (orange line).

The thermal loop is designed to work at constant temperatures and so regulation is available on the flow rates. Concerning the water+glycol loop, regulation is reached through three-way valves installed both on the three single module loops and on the main loop (yellow circles in the figure). The sludge flow, on the other side, is regulated through a variable speed pump (yellow circle) controlled by and inverter.

In order to guarantee a continuous operation of the HRU and avoid the risk of module over-heating, two actions have been implemented:

- All the pumps in the water+glycol loop are doubled and installed in a parallel mode in order to have continuous heat removal also in case of a pump failure.
- The second heat-exchanger is not only connected to the sludge line but also to an industrial water line (light blue line). In case sludges are not available, heat removal is always guaranteed by the possibility to use industrial water in the same heat-exchanger.

The heat-exchanger layout is still under development for both the components. Nominal design temperatures for the HRU are shown on Figure 30.

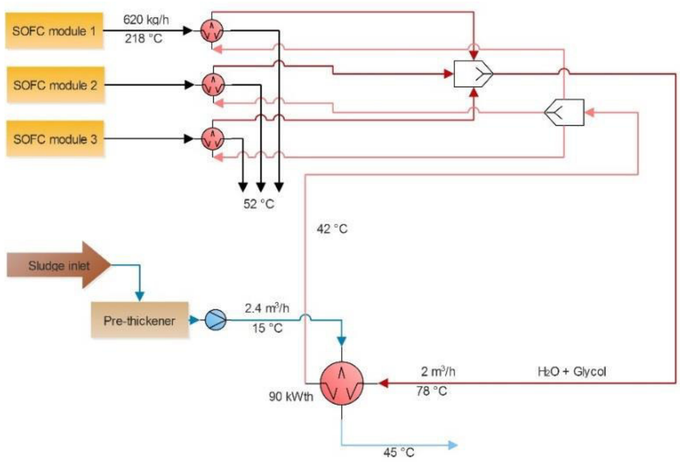


Figure 30. Temperatures on the HRU.

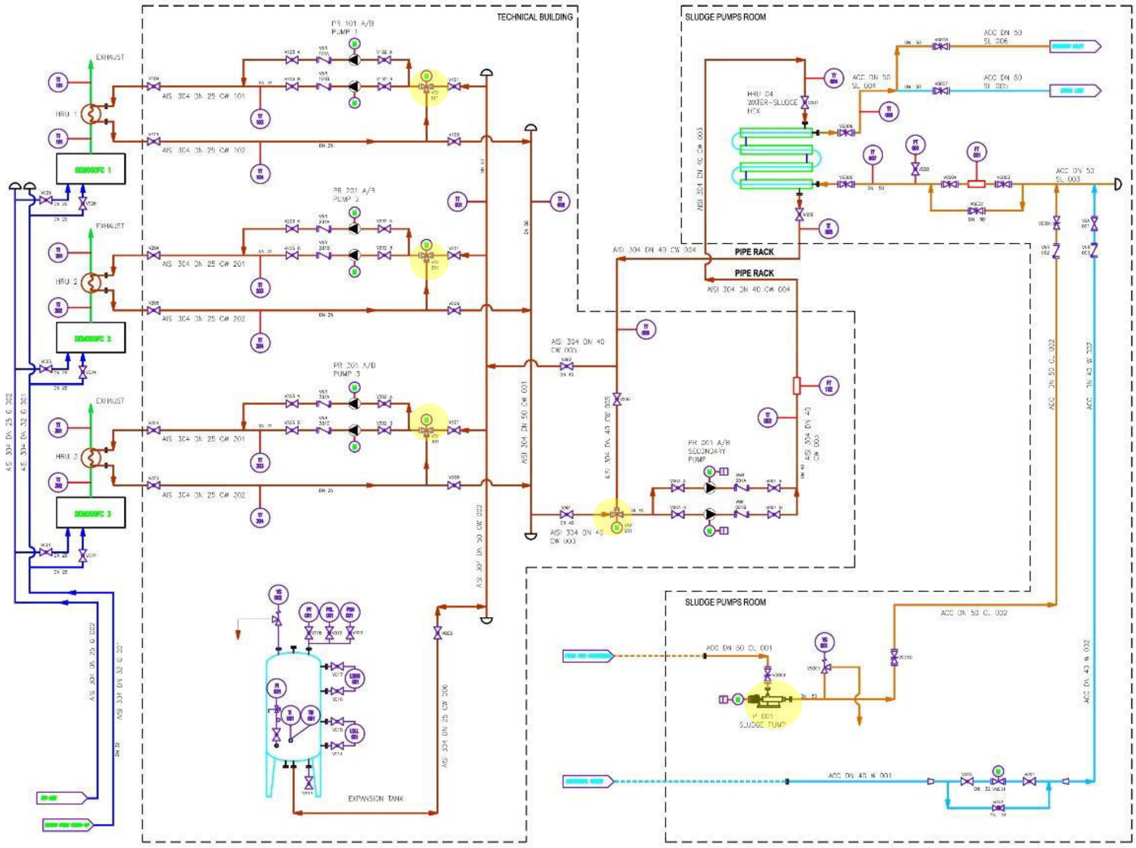


Figure 31. Thermal recovery system.

3.5 Thermal management in the whole plant

The share of digester thermal load coverage between SOFC thermal recovery and natural gas has been deeply discussed in previous deliverables (D2.1 and D2.2).

From an engineering point of view, the existing system will be integrated with the new DEMOSOFC HRU loop. The integration is underlined in the figure below. From the existing sludge line (orange dashed line), a new pipe (orange continuous line) will be detached and connect to the new sludge-water HEX, probably a double pipe heat-exchanger. Part of incoming sludges (flow rate depending on the variable velocity of the feeding pump) are thus sent to the HEX and heated up thanks to the SOFC thermal recovery system (water+glycol loop). The remaining sludge flow is heated in a second, already existing, HEX after being mixed with the recirculation line from the digester. The two flow rates are then mixed again and send to the digester.

The regulation of the heat recovery loop will be guaranteed from the general PLC in order to keep a digester temperature as stable as possible.

On Figure 33 is also shown the total amount of sludge entering the digester. Part of this flow will be, with the DEMOSOFC installation, be sent to the new sludge-water/glycol HEX.

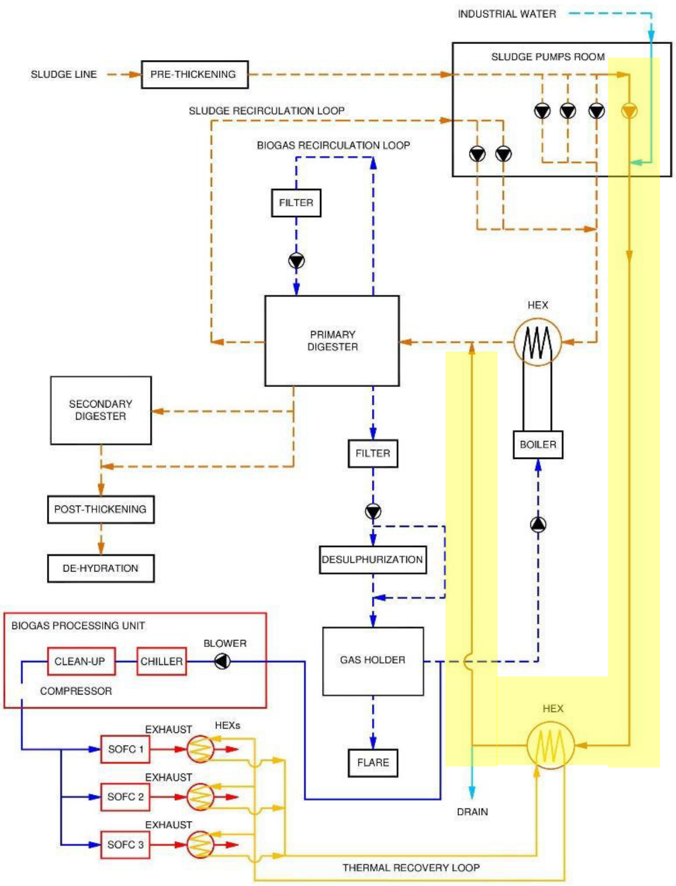


Figure 32. General scheme with focus on the heat integration system.

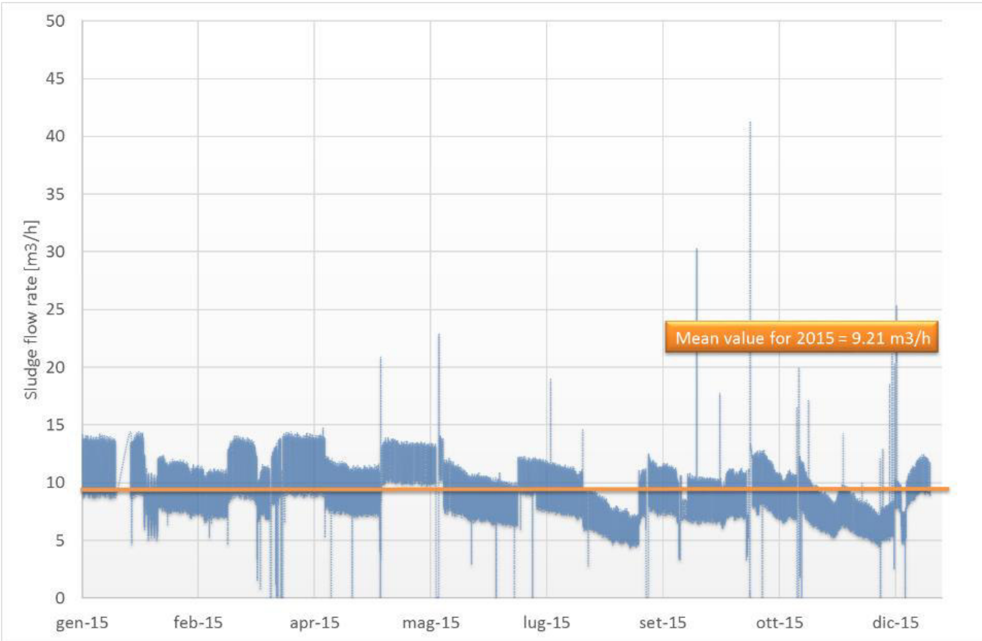


Figure 33. Sludge inlet flow to WWTP.

4. **Inlet and outlet streams**

Inlet and outlet streams are specified in this chapter. SOFC requirements, in terms of biogas supply, air and pressurized air have been already discussed in sub-chapter 3.3. The inlet and outlet streams for each unit are also underlined in Figure 34, where material and energy streams are included. In particular:

- Biogas processing unit
    - Biogas is entering and existing the unit continuously during operation.
    - Adsorbents (activated carbon AC) are replaced every 6-12 months.
    - Nitrogen is required to flush the vessel after the adsorbents substitution.
    - Electrical power is required continuously to run the blower, the chillers and the compressor.
- SOFC modules
    - Clean-up biogas is entering the unit.
    - NH-mix is entering the unit in case the stand-by mode is active.
    - Pressurized air is entering the unit during start-up, modulation phases and shut-down.
    - Nitrogen is required in case of emergency shut-down.
    - Ambient air is continuously entering the unit.
    - Exhaust gas are exiting the unit and going to atmosphere.
    - Electrical power is required during start-up/ shut-down and is produced during operation.
- Heat-recovery unit
    - Sludges or industrial water are entering and exiting the unit
    - Power is required to fed the different pumps and electro-valves.

Specification on the stream (temperature, pressure and flow for the mass streams, voltage for the power streams) have been discussed in the chapter 3 and will be discussed, for what concerning electrical issue, on chapter 5.

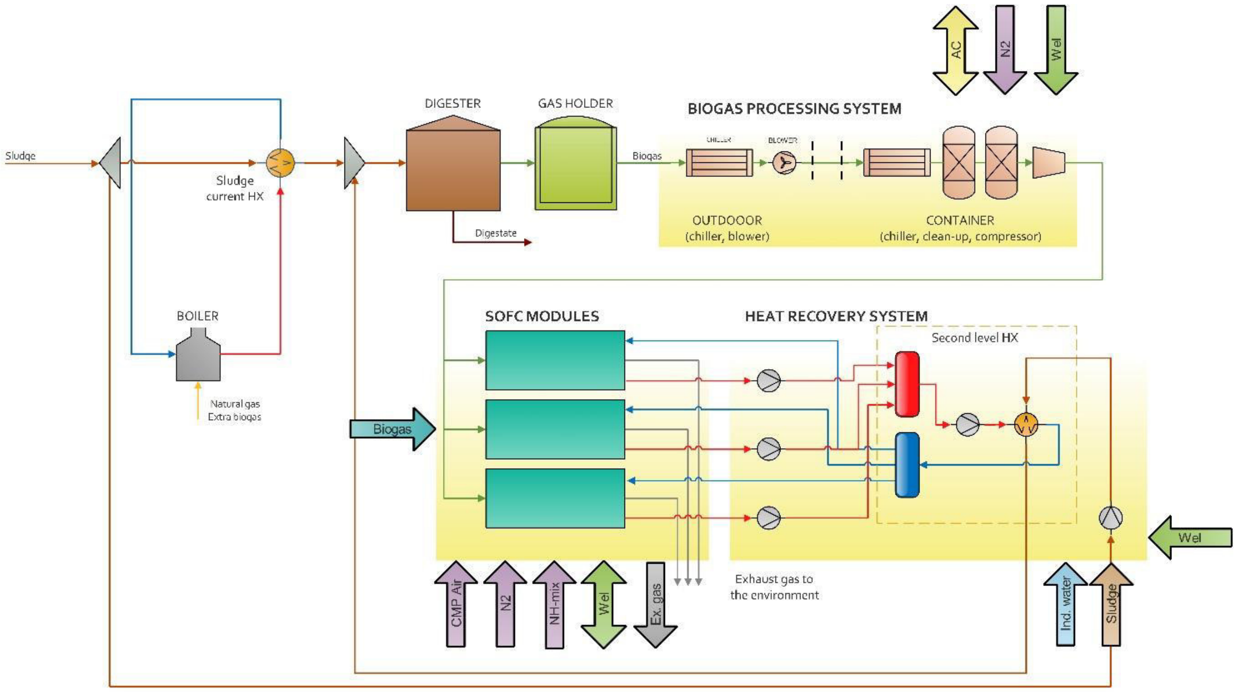


Figure 34. DEMOSOFC layout with focus on inlet/outlet streams.

5. **Electric layout**

DEMOSOFC will implement distributed SOFC electric power production units with capability to operate both in grid-connected and island mode. A planned island may secure electricity during a grid outage for limited amount of loads. Therefore, the electric layout of the installation must deal with the repeatable and a reversible switch from one operating mode to the other.

A schematic of the electric layout is given below.

The most upstream connection of the SOFC modules with the external grid is through the medium voltage (MV) switchgear. A CEI 0-16 protection device is included in the installation. Transformers connect the MV switchgear to the low voltage (LV) one. An underground cable connects the LV switchgear to the DEMOSOFC area. The three SOFC modules are connected to the grid. During the start-up phase, the fuel cell (FC) modules absorb power from the grid, while during normal operation power is exported to the grid. Each SOFC module is equipped with a power measuring device to monitor online the amount of power either absorbed or produced. The detailed electric layout of the SOFC modules, power conditioning cabinets and grid interface cabinet is given in the Appendix F.

In Figure 35 the main auxiliary services (or ancillaries units) of the DEMOSFC installation are shown. These include mainly the clean-up unit (with biogas compressor, chillers and biogas blower), the heat recovery-loop circulation pumps, cooling units for the technical room storing power electronics and electric cabinets, PLC unit, lights, etc. All these auxiliary devices are needed during operation of the SOFC modules. Therefore, when the grid fails (e.g., temporary or even prolonged black.-out event), the SOFC modules will switch from grid-connected to island operating mode, and the FC modules will supply power to them. Hence the SOFC modules not only will cover their own auxiliaries (e.g., cathode air blower, local PLC, etc.), but also the all the other equipment that is needed for functioning of fuel feeding system and heat export system. Basically, in the case of grid failure, the DEMOSFC will enter an extended island operating mode. Since during the switch from grid-connected to island mode the auxiliary services might experience short (<1 sec) power outage, a 50-60 kW battery UPS will be installed as part of the DEMOSOFC installation to handle this transient condition. The estimated maximum power consumption of the auxiliary systems, at full load operation, is less than 50-60 kW electric. Since the net power production of three modules at full load is about three times higher than the consumption of auxiliaries, the SOFC could secure additional critical loads within the WWTP. At the moment, critical loads are still being identified. However several possibilities exist. In the meantime the final choice on the loads to secure is made, the electric layout will be designed and built to allow the connection toward 3-phase loads (as shown in Figure 35).

In the following sections, the SOFC operation modes will be reviewed in detail.

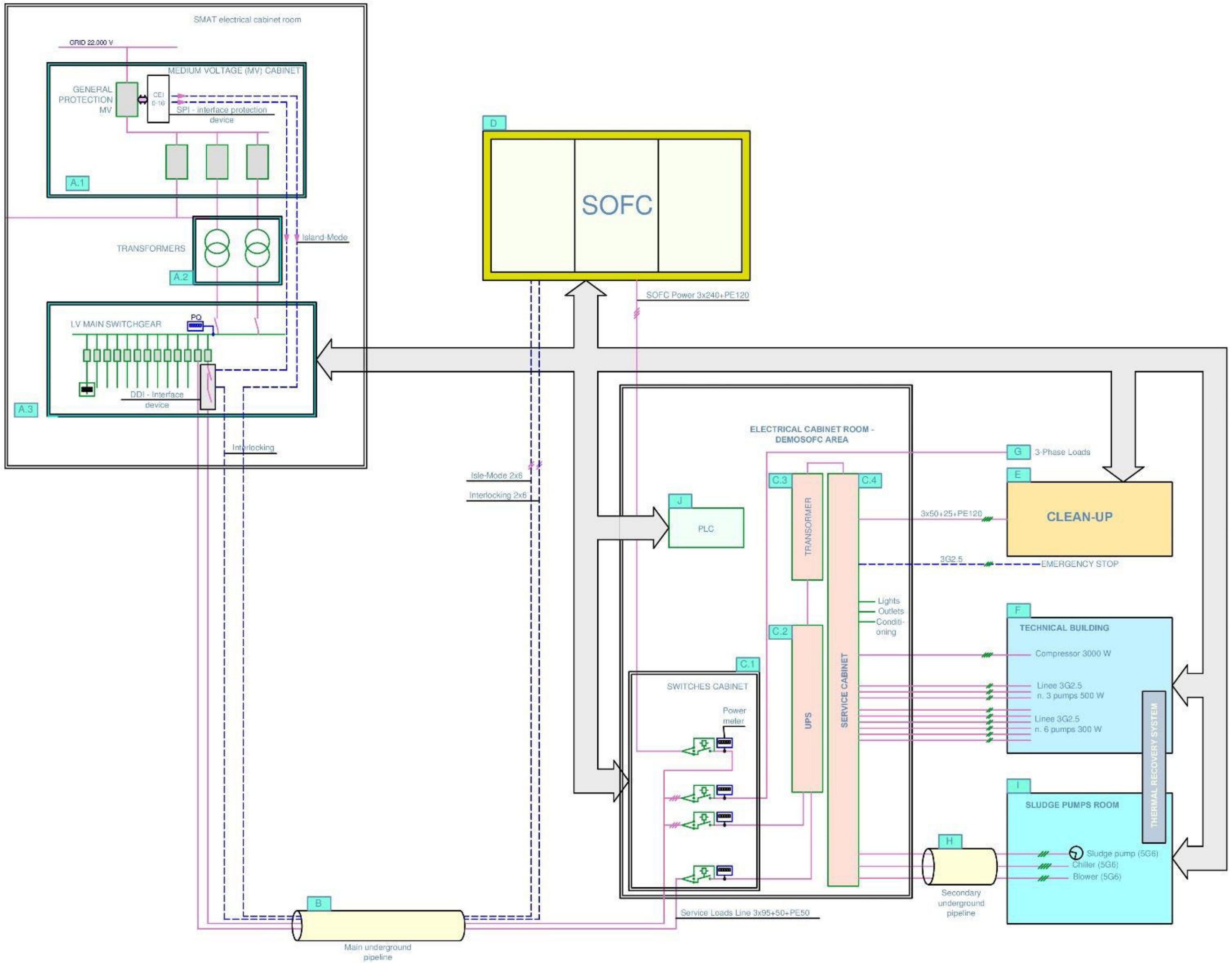


Figure 35. DEMOSOFC electric layout overview.

5.1 Operation Modes

The grid connection of the Convion fuel cell system has two operating modes – Grid paralleled mode and island mode. In grid paralleled mode the fuel cell power is maintained at a given target level and system performance and lifetime is optimized. In island operating mode the system(s) generate a local grid providing limited load following capabilities.

Grid Paralleled Mode

In grid paralleled mode, the system is operated in a mode which minimizes fluctuations in operating conditions. The fuel cell current is controlled according to an externally provided set point [0-100%] and according to following maximum ramp rates:

- Upward: 3% / min;
- Downward: 10% / min.

Current Set point changes can be immediate, ramping and other protection measures are handled internally by the system control logic. Fuel cell temperature and other factors may further constrain the achievable upward ramp rate. In some cases it may not be possible to reach 100% fuel cell current.

The power output of the system with a given fuel cell current depends on fuel cell efficiency and auxiliary power consumption such as cooling need, which vary over time. To maximize the system lifetime and optimize the usability of data acquired from the system it is advisable to keep the current set point constant or as steady as possible and preferably in the range of 60-100%.

Island Mode

In island mode, the system is capable of generating a local 400V, 50Hz three-phase IT-grid which can be used to supply relevant on-side loads. The system can only enter island mode after it has been started up in grid paralleled mode. Operation in island mode further requires that site functions essential to the operation are maintained namely:

- Fuel pressurization and pre-cleaning
- Pressurized air supply
- Cooling of power electronics
- Heat recovery

The island grid can itself be used to provide the electrical power needed for the above listed functions. Note that there is an interruption in power supply of approximately one seconds in the change-over from grid paralleled to island mode. For this reason a battery UPS is include in the DEMOSOFC installation.

Change in between the grid parallel and island modes are made in accordance with standards VDE-AR-N4105 (German low-voltage grid-code), BDEW (German medium-voltage grid-code), or CEI 0-21 (Italian low voltage grid-code). Customization for rules of mode changes can be made within limitations of hardware of a grid protection relay.

As the fuel cells lack inertia, the fuel cell system has very limited power surge capabilities in island mode.

The following limitations apply:

1) The peak power demand of the island must not exceed the nominal power output of the system.
2) The peak power demand of the island must not exceed the power previously supplied by the system in grid paralleled mode. For power ramp up, the ramp rate given specified for grid paralleled mode applies.
3) Power demand transients shall be limited to 20kW peak to peak, average ± 10kW for each C50 unit in operation, i.e. 60kW peak to peak / average ± 30 kW for three paralleled C50 systems.

Each C50 unit is controlled to provide a ± 10 kW immediate response capability around average (=baseline) power demand. Power demands in excess of this cannot be supplied. Power levels below this range will shift the baseline level downward.

Transition from/to grid-parallel mode to/from island mode

The transition from one operating mode to another is controlled by two signals:

i) the ‘island mode’ signal, which manages the connection or disconnection from the grid by either closing or opening a series of contactors, and;
ii) the ‘interlocking’ signal, which manages the time at which the SOFC is reconnected to the grid. The interlocking signal is electronically controlled at the grid contactors with the following type of device (Figure 36).

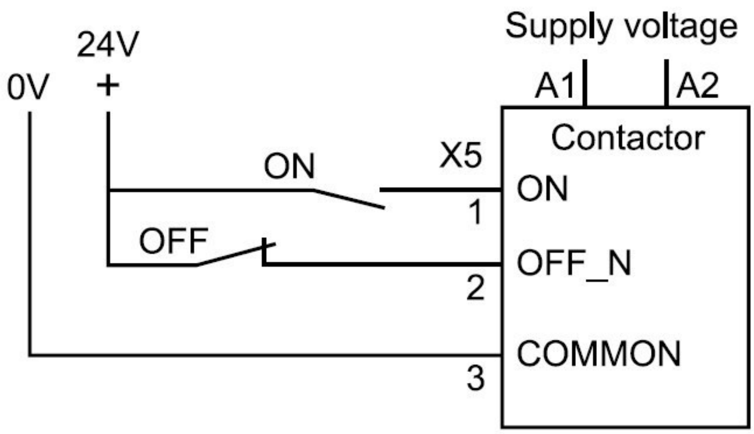


Figure 36. Example of an electronic control of a grid contactor (for further detail refer to ABB AF460-30-11)

The normal-open ON contact is at the mains protection device. The normal-closed OFF contact is at the CONVION I/O. In this interlocking case, MAINS PROTECTION ON signal is required to avoid non-active logic at the islanding of the SOFC system. Note that the mains protection is assumed to have secured power supply (UPS) in order to prevent the island mode to be a failure mode.

The 'grid parallel mode' request (normally open) is managed by a signal generated from the mains protection device to the CONVION I/O interface. The following conditions hold:

- 24V – GRID PARALLEL MODE
- 0V – ISLAND MODE

Therefore a signal of 24 V is required to activate the grid connected operation mode. 0 V is instead for island mode. The 'interlocking' mains protection (normally closed) are in charge of delaying the reclose of the grid contactors.

The 'island mode request' is managed instead by the plant PLC (normally open); a signal is sent from the plant PLC to the SOFC system that opens the interlocking mains protection circuit to grid contactors.

The following conditions hold:

- MAINS PROTECTION ON
- 24V – ON STATE
- 0V – OFF STATE (NON-OPERATIVE)

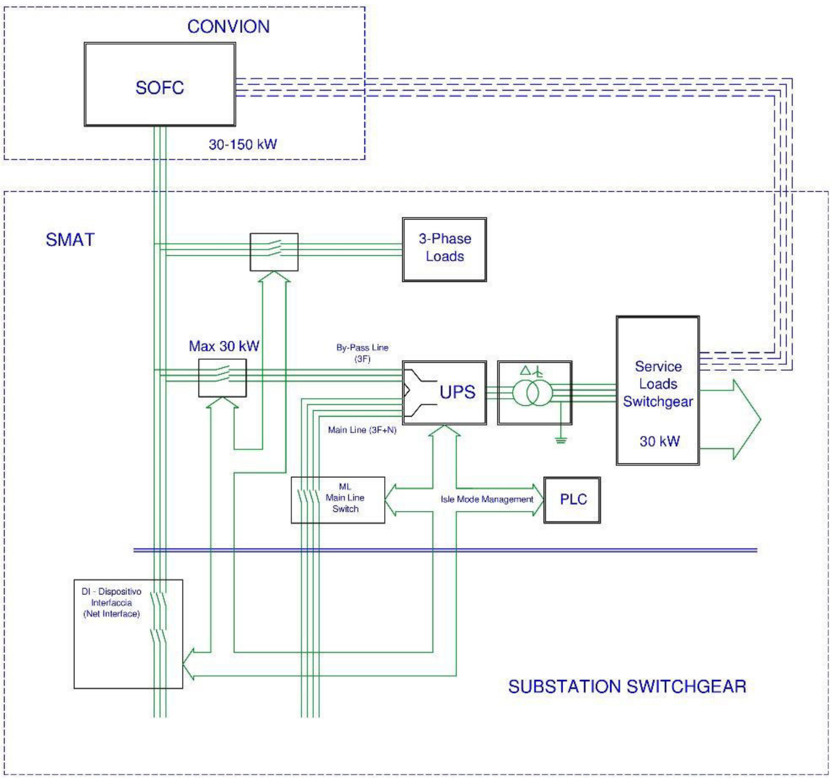
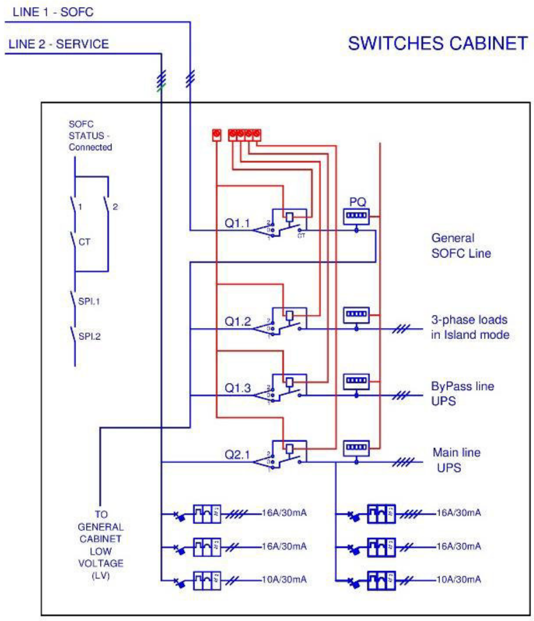


Figure 37. Simplified electrical scheme.



		Switch 1-0-2	Contactor
Q1.1	Inlet line SOFC	500 A	500 A
Q1.2	3-phase loads in Island mode	500 A	500 A
Q1.3	ByPass line UPS	250 A	250 A
Q2.1	Main line UPS	250 A	250 A
	Multifunction tool to measure currents , powers. Possibility of remote connection for periodic data logging		
PQ	Multifunction tool to measure currents , powers and functions of POWER QUALITY , remote connection for data logging		

Figure 38. Switches cabinet details.

6. Logic of control of the DEMO & signals

The DEMOSOFC control system will include different section, controlled and connected through a general PLC system. Different units and data exchange are shown from Figure 40 to Figure 43:

- SOFC section. The modules will be internally controlled by a dedicated control system from Convion. Data will be exchanged related to main parameters on SOFC performance and alarm signals.
- Clean-up unit. The container will have its electrical cabinet and control system for what concerning the compressor internal regulation. Data will be anyway exchanged to control the system.
- Thermal recovery section is referred to the first HEX, gas – water/glycol, placed inside the modules. Data on the flow rates, temperatures and pressures will be exchanged to measure the effective thermal power recovered.
- Gas analyser. The system will be connected directly to the SOFC modules which will generate alarms in case of sulphur and silicon values beyond the limits.
- Gas holder. The main plant control loop is based on the gas holder level measurement, which will be used to define the SOFC power output depending on the biogas availability, through a PID controller (see Figure 39).
- SMAT HEX is the section referred to the water/glycol – sludge heat exchanger.
- Island mode. This is the signal referred to the island mode request (by grid disconnection or manually, for an island mode test)
- Air conditioning. The air conditioning system will also be controlled, especially for what concerning the electrical cabinet room.
- SPI/ATEX. This section is related to safety/ alarm signals.

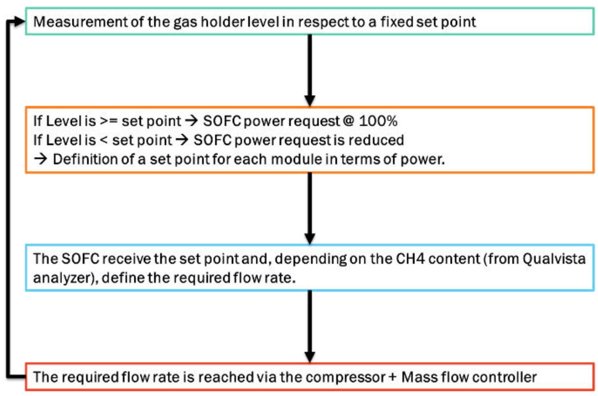


Figure 39. Main control loop between gas holder level measurement and SOFC requested electrical power output.

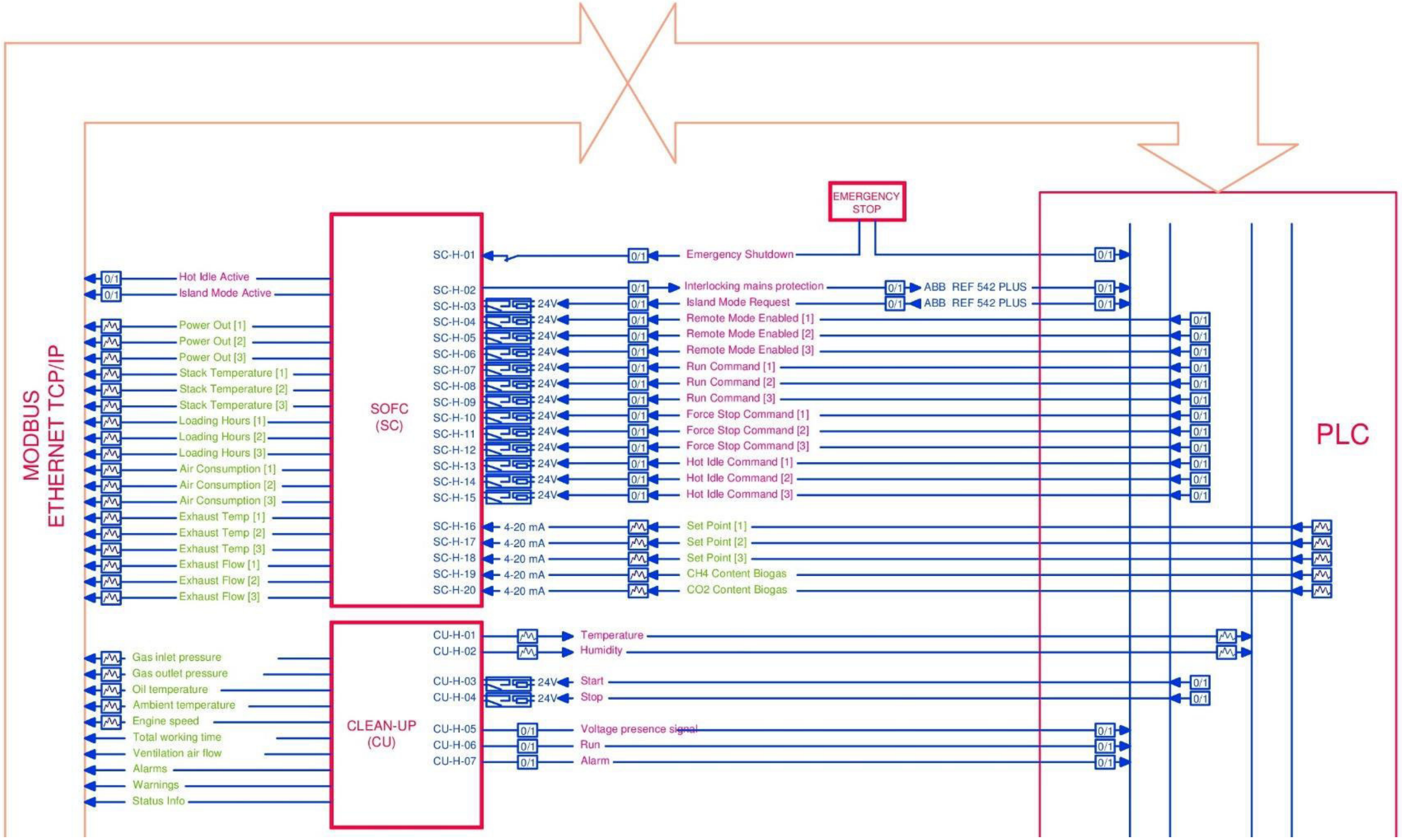


Figure 40. SOFC and CLEAN-UP sections signal list.

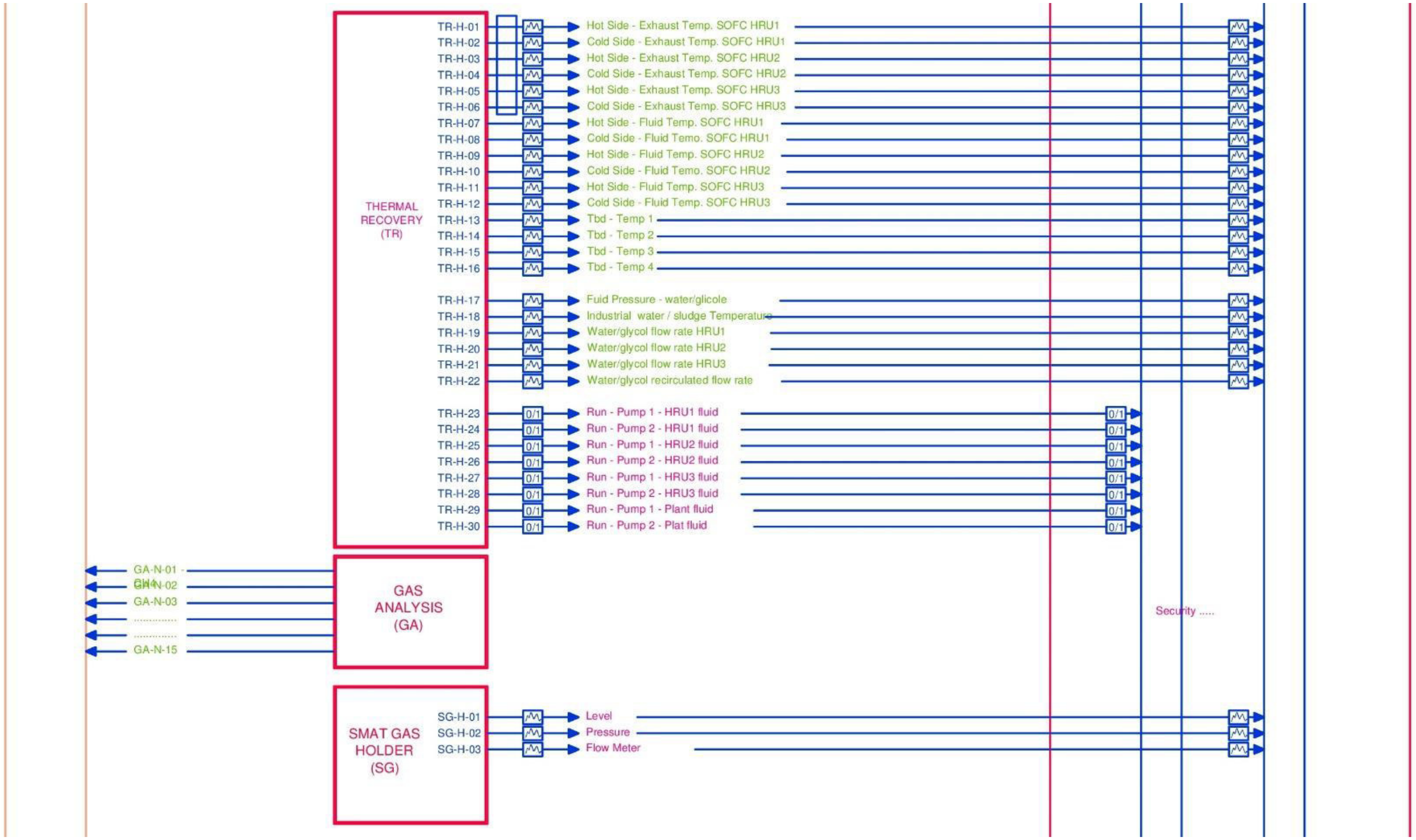


Figure 41. Thermal recovery, gas analyser and gas holder sections signal list.

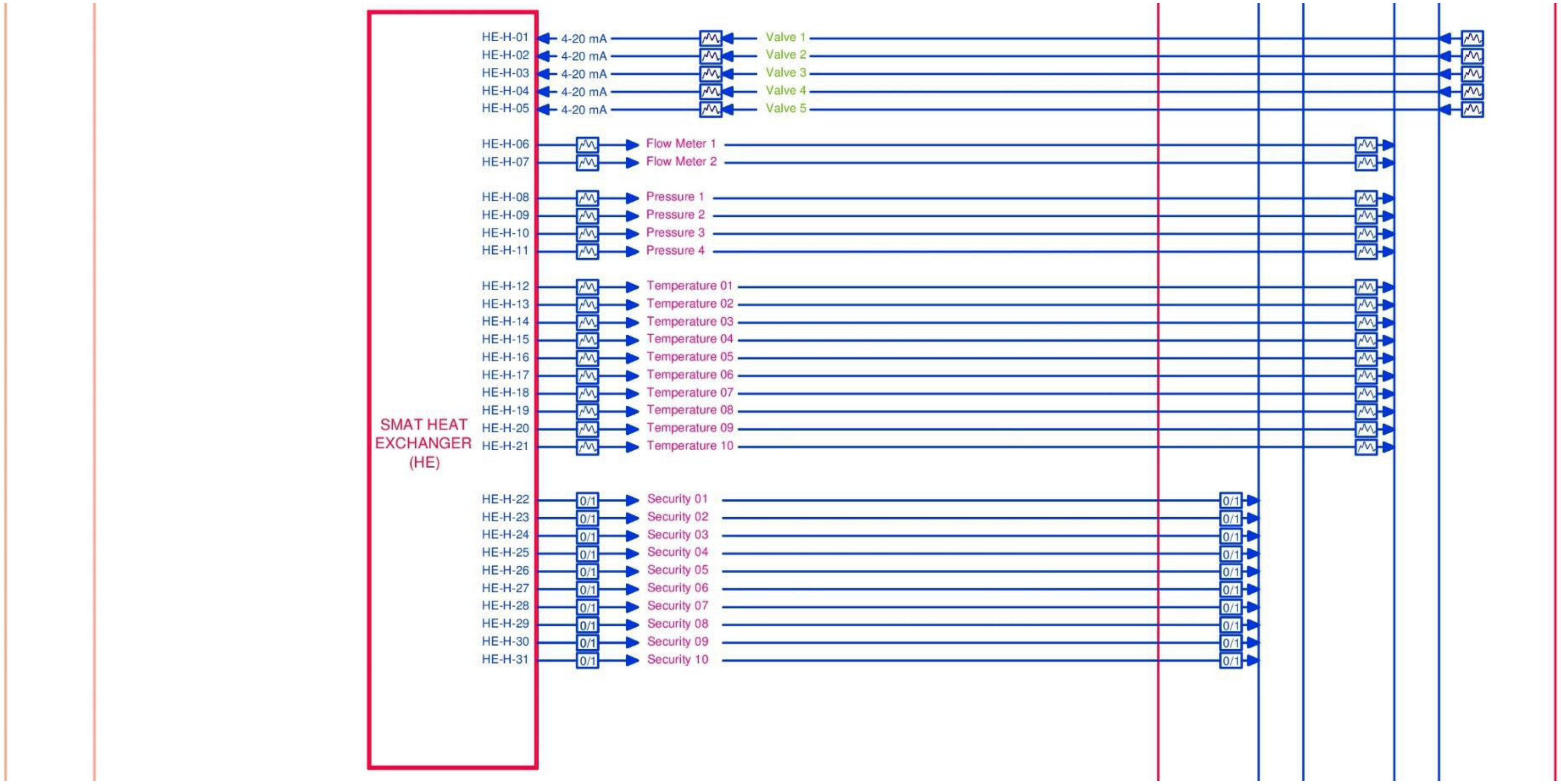


Figure 42. SMAT HEX section signal list.

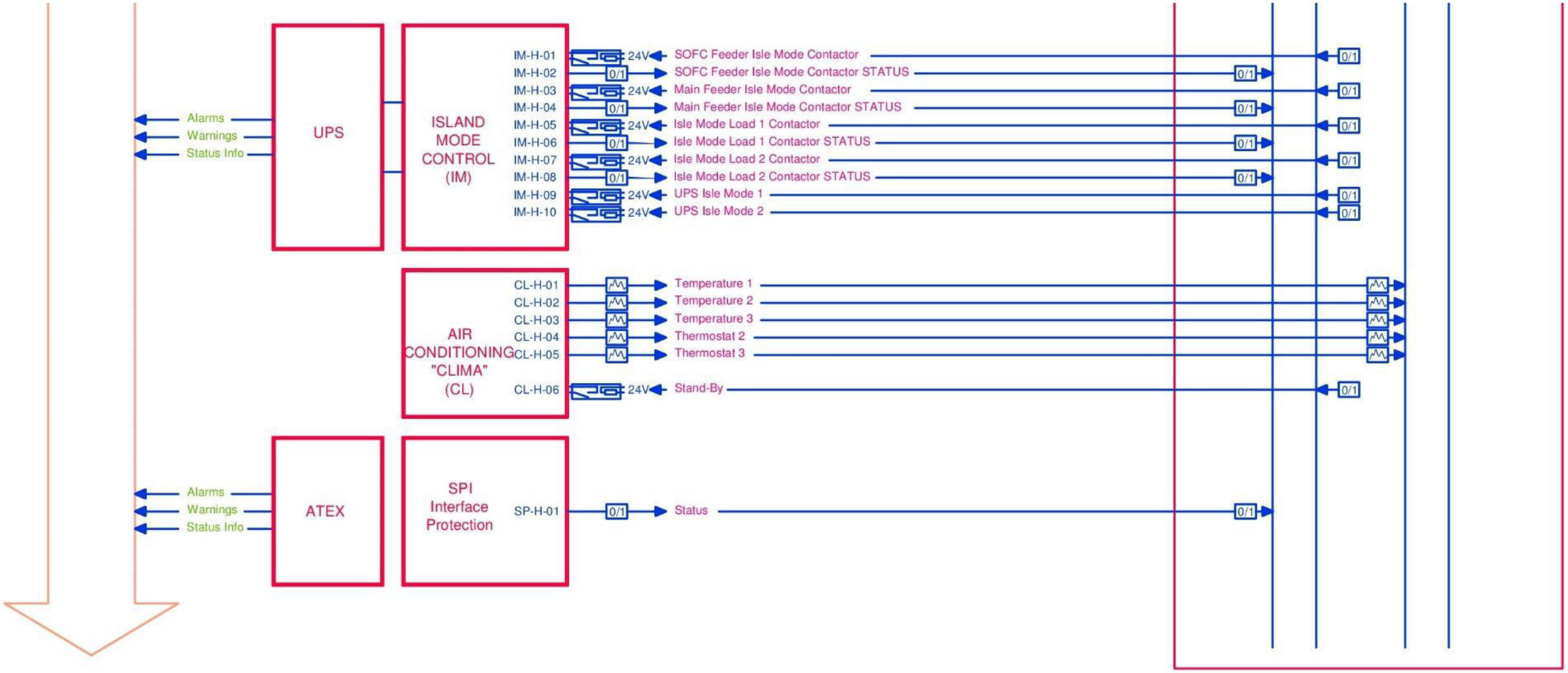
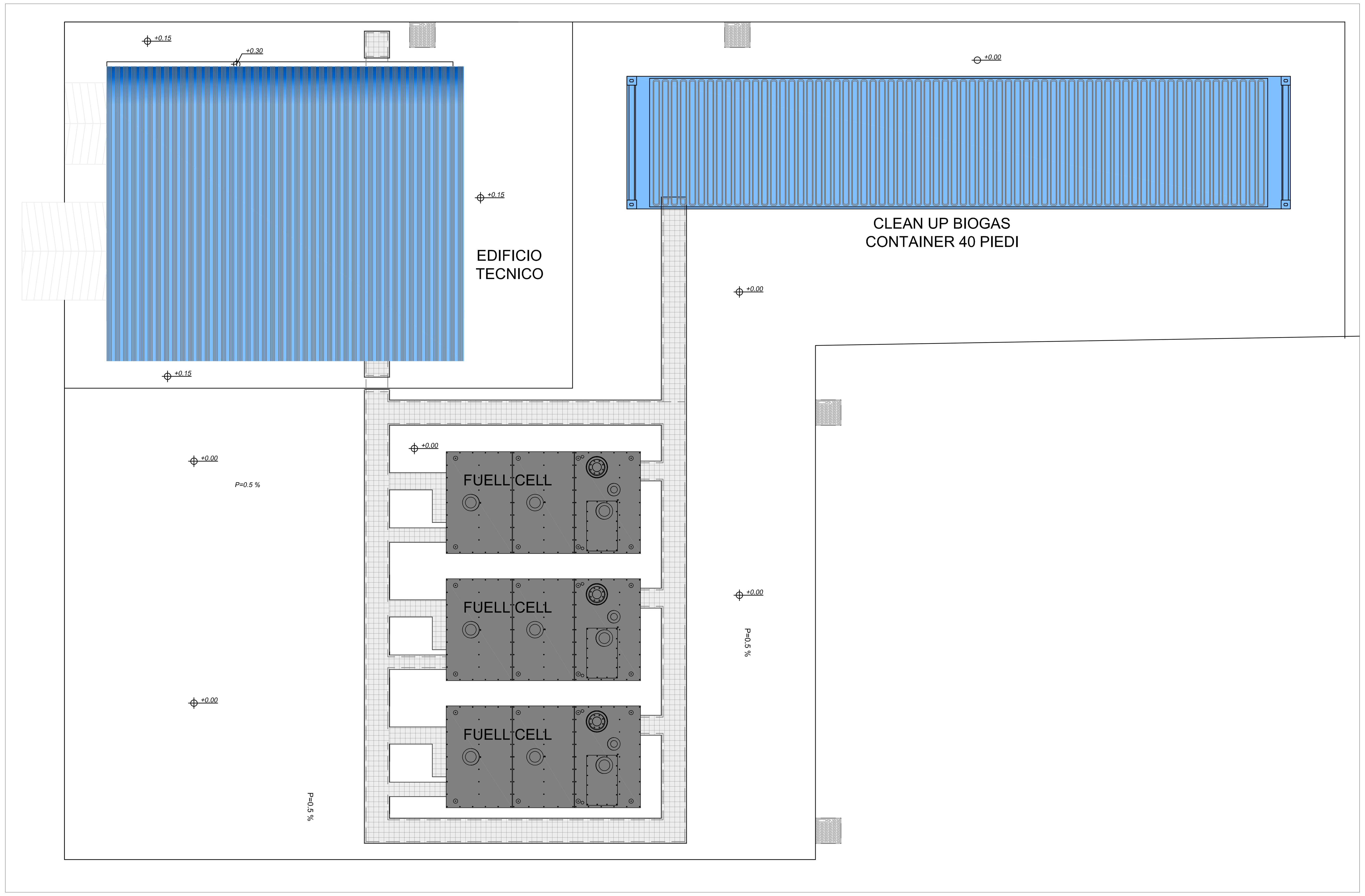


Figure 43. Island mode, Air conditioning and SPI/ATEX sections signal list.

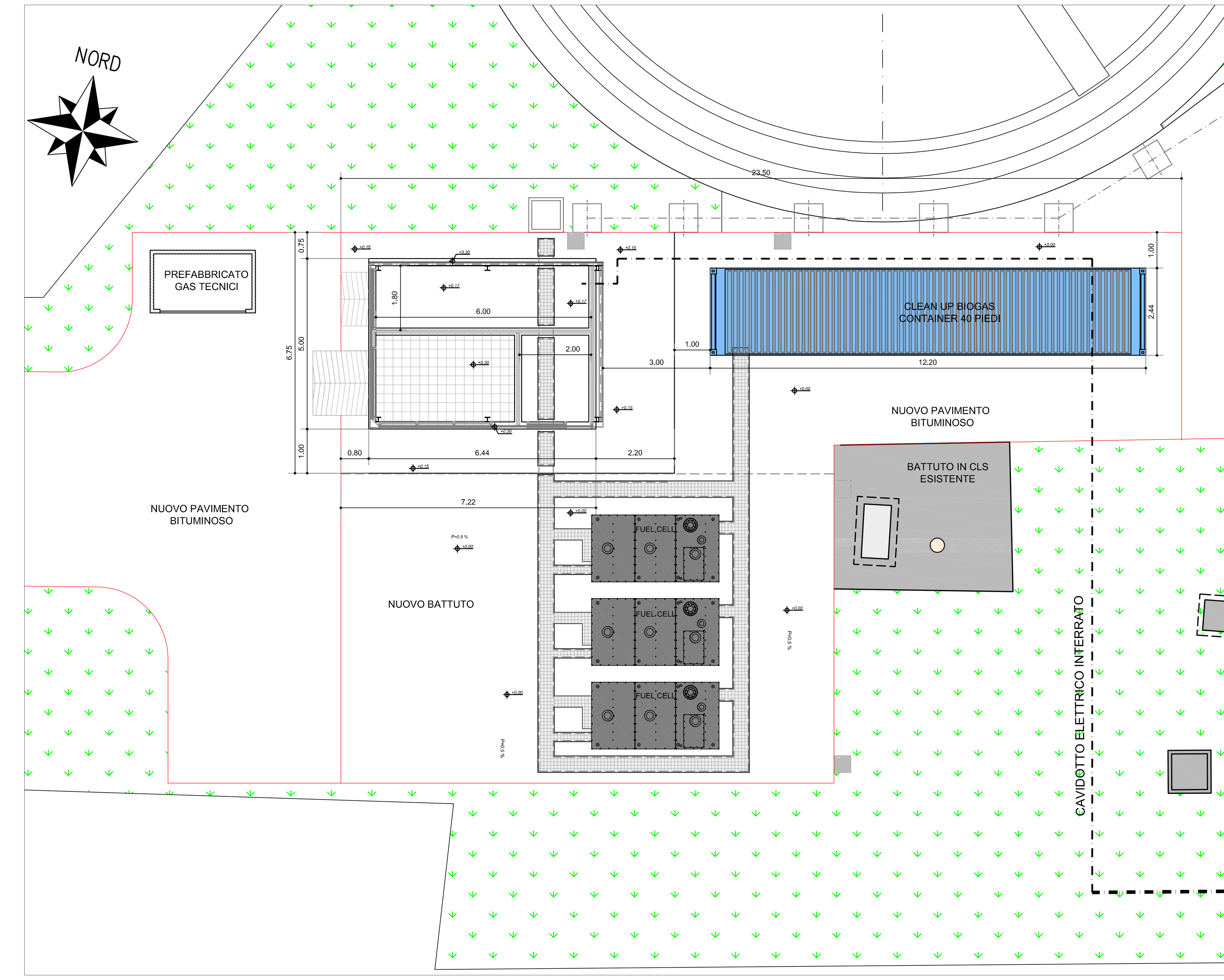
7. **Appendix**

7.1 Appendix A – "AREA DI INTERVENTO – PIANTE E PROSPETTI"

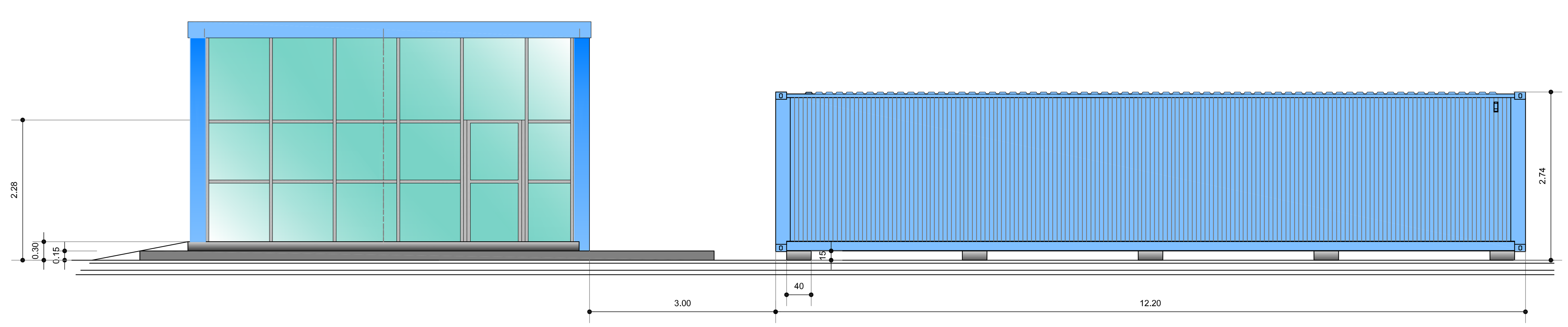
PIANTA COPERTURE - SCALA 1:50 -



PLANIMETRIA GENERALE - SCALA 1:100 -

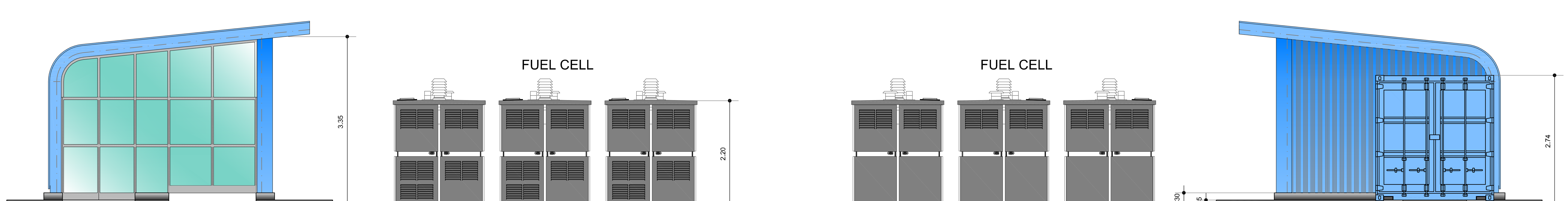


PROSPETTO SUD - SCALA 1:50 -



PROSPETTO OVEST - SCALA 1:50 -

PROSPETTO EST - SCALA 1:50 -



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PROG. N° -

PROGETTO DEFINITIVO

Comuni di Collegno

PROGETTO DEMOSOFC

AREA DI INTERVENTO - PIANTE E PROSPETTI

OPERE IMPIANTISTICHE

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il Direttore Generale
Dott. Ing. Marco Acri

REV.	DESCRIZIONE	DATA	REDAZIONE	VERIFICA	APPROVAZIONE
3					
2					
1					
0	EMISSIONE	MARZO 2016	TROIANO	VAUDANO	VAUDANO

documento n°: 03

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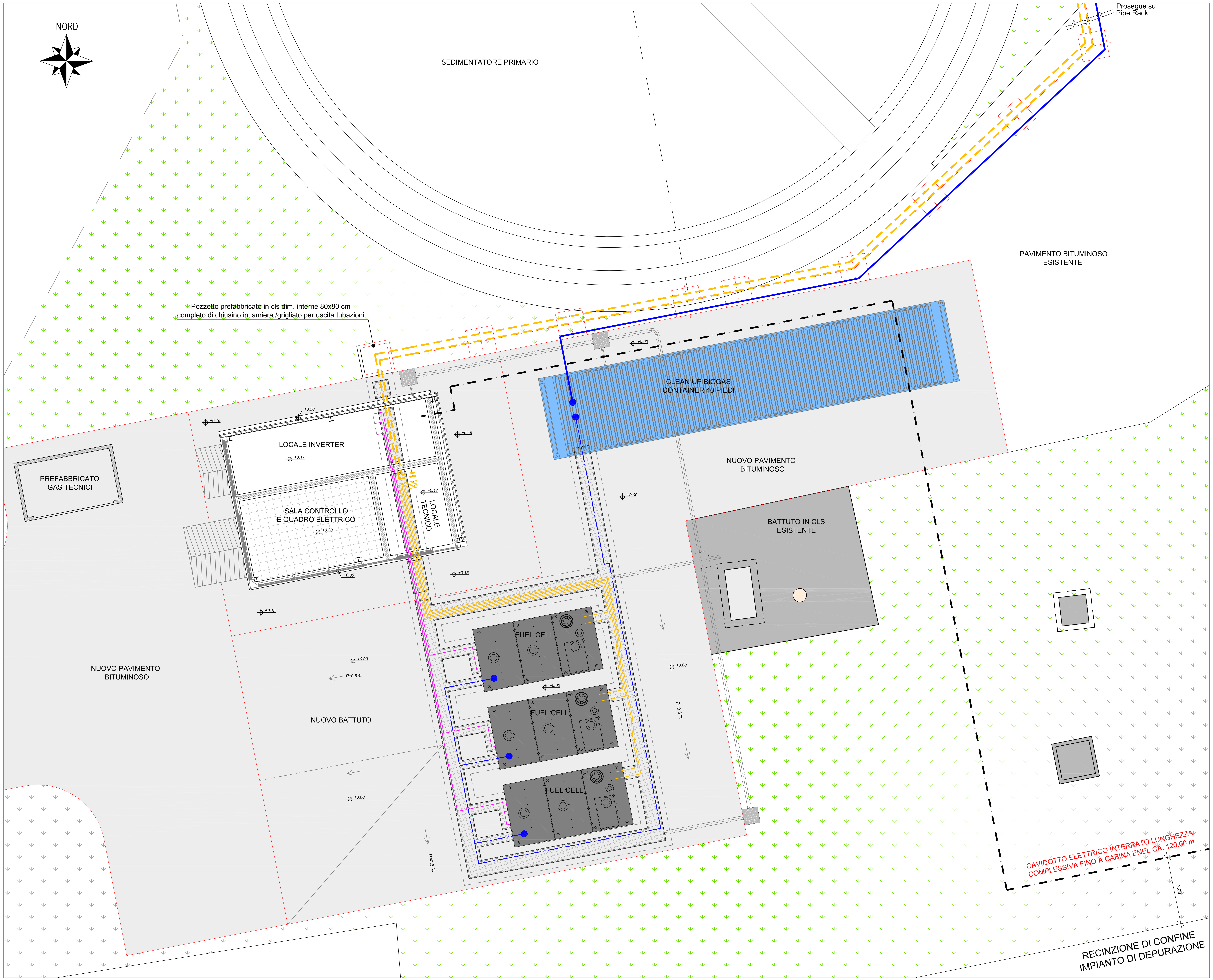
PRGMO0012/G

7.2 Appendix B – ""PLANIMETRIA GENERALE IMPIANTI E LINEE – AREA DI INTERVENTI"



LEGENDA

- LINEA CAVI LOCALE INVERTER (n° 3 cavi per ogni Fuel cell)
- LINEA HRU RECUPERO TERMICO (n° 2 tubi DN 25 per ogni Fuel cell)
- LINEA HRU RECUPERO TERMICO (n° 2 tubi DN 40 incamiciato DN 80)
- LINEA GAS DN 25
- LINEA GAS DN 50

VALVOLA A SFERA
VALVOLA A SARACINESCA
VALVOLA A GHIGLIOTTINA
VALVOLA A TRE VIE
VALVOLA NON RITORNO
VALVOLA (GENERICA) FLANGIATA
VALVOLA DI SICUREZZA
SONDA TEMPERATURA
SONDA PRESSIONE
MISURATORE PORTATA
MOTORE

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PROG. N° - PROGETTO DEFINITIVO

Comuni di Collegno

PROGETTO DEMOSOFC

PLANIMETRIA GENERALE IMPIANTI E LINEE AREA DI INTERVENTI

SCALA 1:50

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1					
0	EMISSIONE	MARZO 2016	TROIANO	VAUDANO	VAUDANO

documento n°: 04

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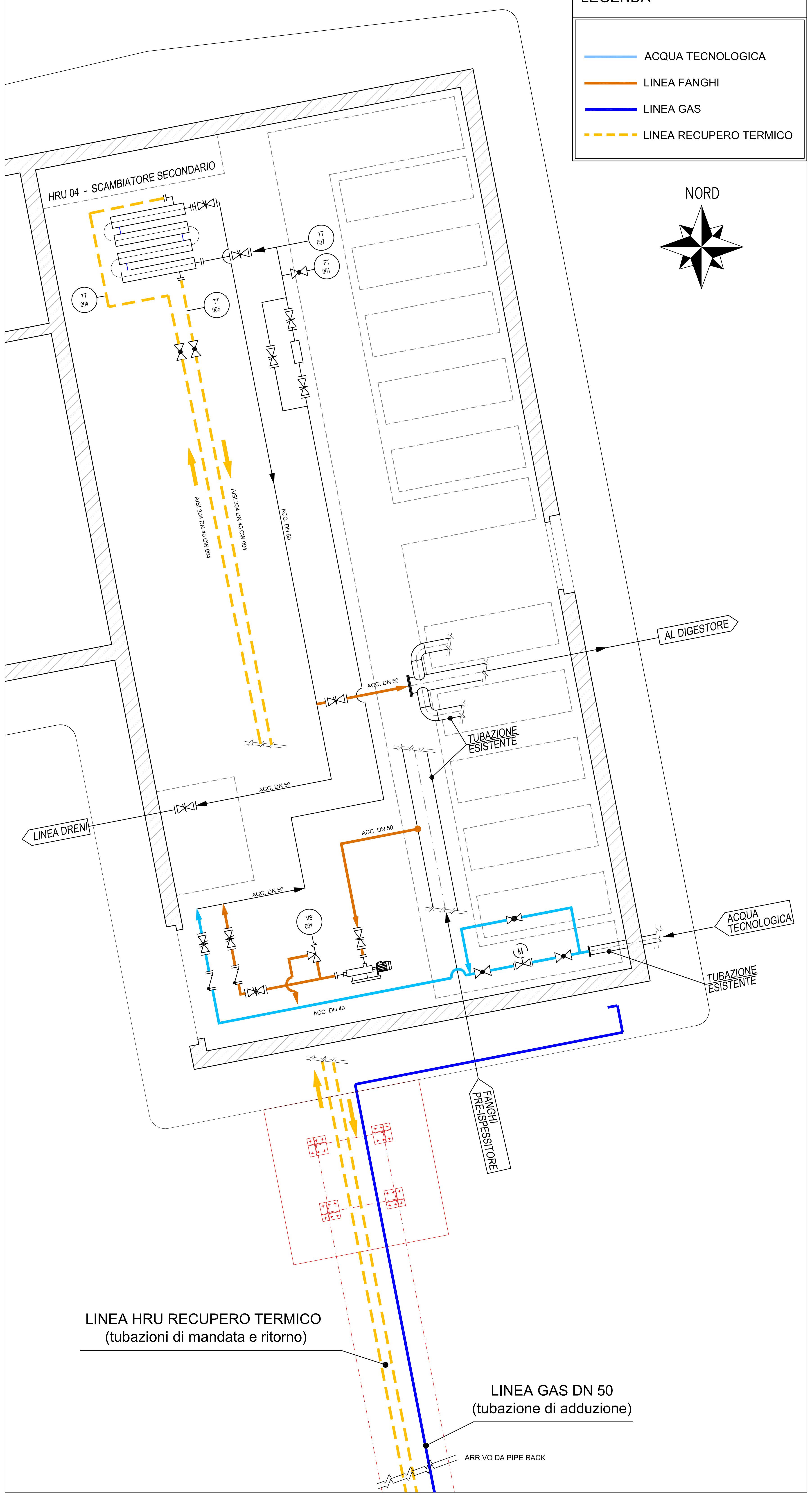
PRGMO0012/G

7.3 Appendix C – "PLANIMETRIA GENERALE IMPIANTI E LINEE LOCALE POMPE FANGHI ESISTENTE – OPERE IMPIANTISTICHE"

LOCALE POMPE FANGHI



LEGENDA

azzurra continua	ACQUA TECNOLOGICA
arancione continua	LINEA FANGHI
blu continua	LINEA GAS
gialla tratteggiata	LINEA RECUPERO TERMICO

LOCALE POMPE FANGHI (QUOTA COPERTURA)

LEGENDA

nera tratteggiata	LINEA GAS ESISTENTE
blu continua	LINEA GAS IN PROGETTO

LEGENDA

magenta continua	LINEA CAVI LOCALE INVERTER (n° 3 cavi per ogni Fuel cell)
gialla continua	LINEA HRU RECUPERO TERMICO (n° 2 tubi DN 25 per ogni Fuel cell)
gialla tratteggiata	LINEA HRU RECUPERO TERMICO (n° 2 tubi DN 40 incamiciato DN 80)
blu tratto-punto	LINEA GAS DN 25
blu continua	LINEA GAS DN 50

	VALVOLA A SFERA
	VALVOLA A SARACINESCA
	VALVOLA A GHIGLIOTTINA
	VALVOLA A TRE VIE
	VALVOLA NON RITORNO
	VALVOLA (GENERICA) FLANGIATA
	VALVOLA DI SICUREZZA
TT	*SONDA TEMPERATURA*
PT	*SONDA PRESSIONE*
FT	*MISURATORE PORTATA*
M	*MOTORE*

Autorità d'ambito Torinese 3
Autorità d'ambito Torinese A.T.O.3

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PROG. N° - PROGETTO DEFINITIVO

Comuni di Collegno

PROGETTO DEMOSOFC

PLANIMETRIA GENERALE IMPIANTI E LINEE
LOCALE POMPE FANGHI ESISTENTE

SCALA 1:50

OPERE IMPIANTISTICHE

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Dott. Ing. Marco Acri

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3					
2					
1					
0	EMISSIONE	MARZO 2016	TROIANO	VAUDANO	VAUDANO

documento n°: 05

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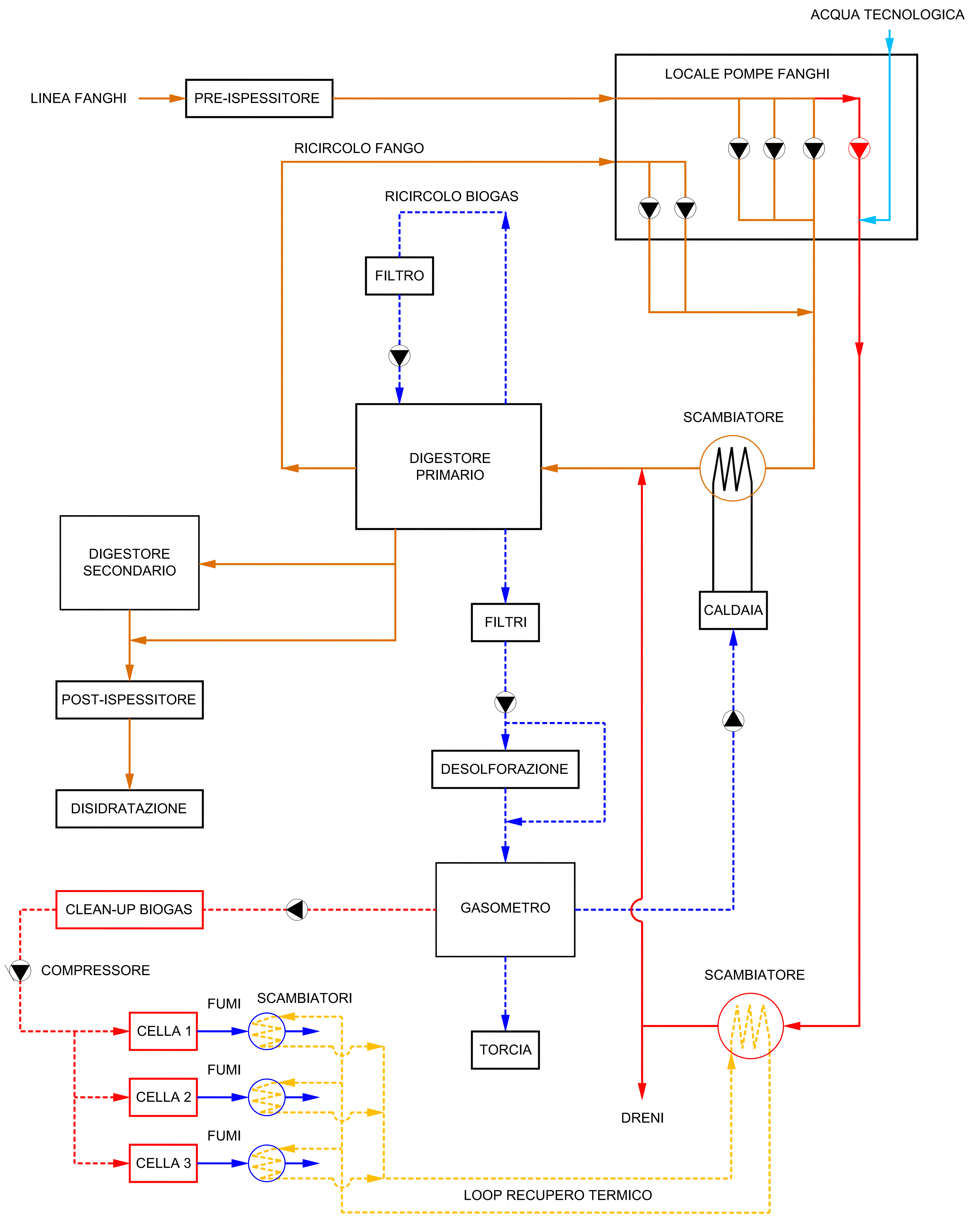
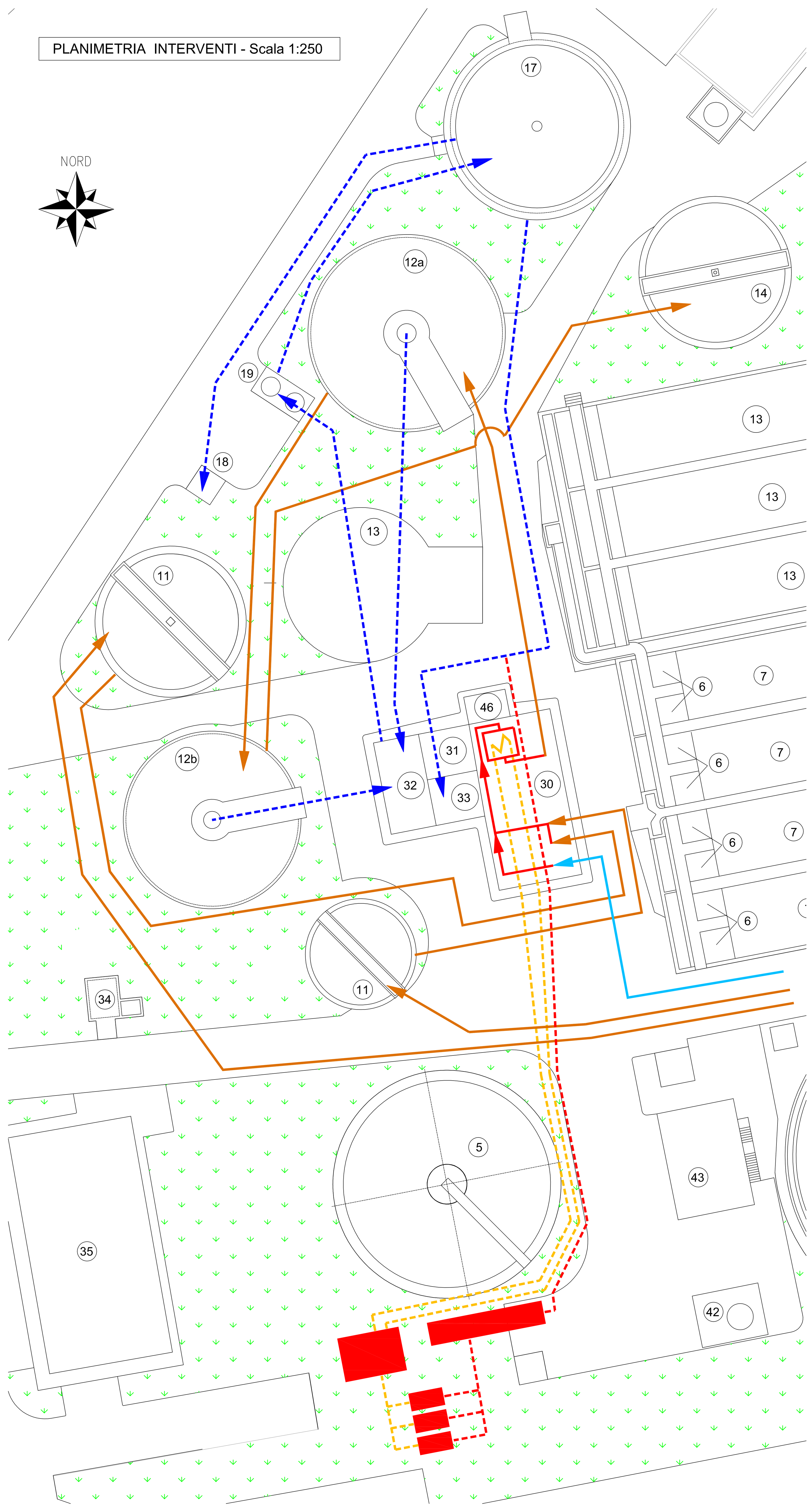
PROGETTO	ID R.I.	documento (file)
- -	RI0411	SOFC-DEF-02_04_05

7.4 Appendix D – "P&ID GENERALE DEGLI INTERVENTI – OPERE IMPIANTISTICHE"





LEGENDA IMPIANTO

01 - INGRESSO LIQUAMI - MISURA PORTATA	25 - OFFICINA MECCANICA
02 - GRIGLIATURA - COMPATTAZIONE	26 - MAGAZZINO /AUTO RIMESSA
03 - DISSABBIATURA	27 - LOCALE COMPRESSORI HV TURBO
04 - FLOCCULAZIONE	28 - CABINA2 TRASFO QL2
05 - SEDIMENTAZIONE PRIMARIA	29 - DOSAGGIO CLORO/ ANTINCENDIO
06 - DENITRIFICAZIONE	30 - LOCALE POMPE FANGHI
07 - OSSIDAZIONE	31 - LOCALE COMPRESSORI BIOGAS
08 - SEDIMENTAZIONE FINALE	32 - LOCALE FILTRAZIONE BIOGAS
09 - USCITA LIQUAMI - MISURA PORTATA	33 - CENTRALE TERMICA
10 - CLORAZIONE	34 - POZZETTO RILANCIO DRENI
11 - PREISPESSITORE	35 - NUOVA PALAZZINA UFFICI
12a - DIGESTORE PRIMARIO Fisia	36a - QUADRO ELETTRICO LOCALE 1/3
12b - DIGESTORE PRIMARIO Casta.	36b - SALA OPERATORI
13 - STOCCAGGIO PERCOLATO	36c - MAGAZZINO OLI
14 - POST ISPESSITORE	37 - PALAZZINA SERVIZI
15 - DISIDRATAZIONE MECCANICA FANGHI	38 - TETTOIA POSTEGGIO
16 - PESA	39 - INGRESSO IMPIANTO
17 - GASOMETRO	40a - DEODORIZZAZIONE 1
18 - FIACCOLA	40b - DEODORIZZAZIONE 2
19 - DESOLFORAZIONE BIOGAS	41 - IMPIANTO DI FILTRAZIONE E RIUTILIZZO
20 - CABINA1 ENEL - TRASFORMATORI	42 - PIAZZOLA OSSIGENO
21 - LOCALE REAGENTI	43 - OZONIZZAZIONE FANGHI
22 - EX TRASFORMATORI	44 - POZZO DORA
23 - OFFICINA ELETTRICA	45 - TORRE PIEZOMETRICA
24 - ELETTROGENERATORE	46 - QUADRO ELETTRICO LOCALE 5

LEGENDA NUOVI INTERVENTI

- EDIFICIO TECNICO
- FUEL CELL
- IMPIANTO BIOGAS CLEANING
- LINEA FANGHI (esistente)
- LINEA BIOGAS (esistente)
- LINEA ACQUA TECNOLOGICA (esistente)
- LINEA FANGHI (nuova opera)
- LINEA BIOGAS (nuova opera)
- LINEE RECUPERO TERMICO (nuove opere)

Autorità d'ambito Torinese 3

Autorità d'ambito Torinese A.T.O.3

smat gruppo

PROG. N° - PROGETTO DEFINITIVO

Comuni di Collegno

PROGETTO DEMOSOFC

P&ID

GENERALE DEGLI INTERVENTI

OPERE IMPIANTISTICHE

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il Direttore Generale
Dott. Ing. Marco Acri

REV.	DESCRIZIONE	DATA	REDAZIONE	VERIFICA	APPROVAZIONE
3					
2					
1					
0	EMISSIONE	MARZO 2016	TROIANO	VAUDANO	VAUDANO

documento n°: 06

Progettista: Ing. Giorgio VAUDANO
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Collaboratore : P.ind. Marco TROIANO

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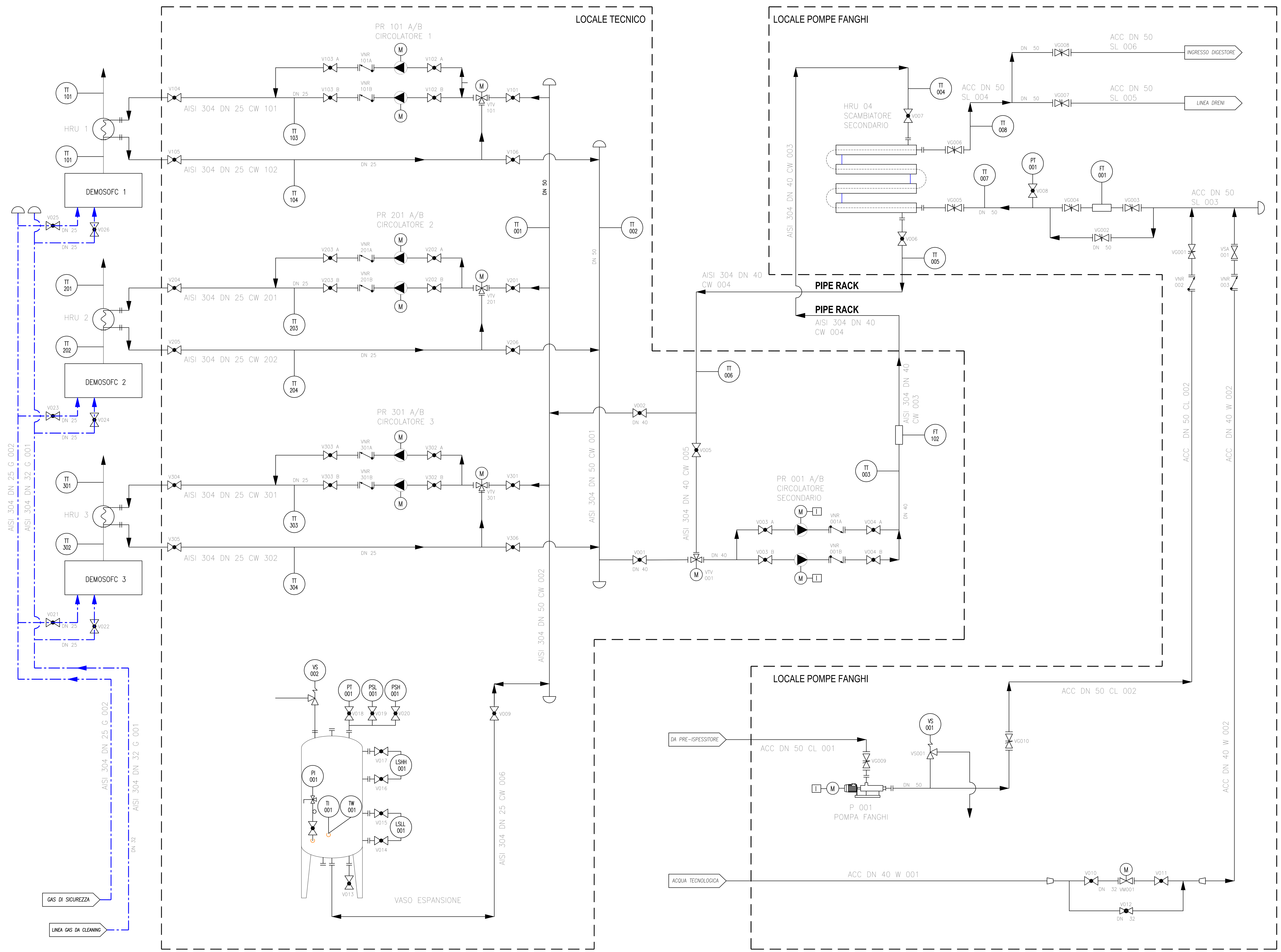
Risorse Idriche

PROGETTO	ID R.I.	documento (file:)
- -	RI0411	SOFC-DEF-06_P&ID Generale

PRGMO0012/G

7.5 Appendix E – "RECUPERO TERMICO"



LEGENDA

	VALVOLA A SFERA
	VALVOLA A SARACINESCA
	VALVOLA A GHIGLIOTTINA
	VALVOLA A TRE VIE
	VALVOLA NON RITORNO
	VALVOLA (GENERICA) FLANGIATA
	VALVOLA DI SICUREZZA
TT	SONDA TEMPERATURA
PT	SONDA PRESSIONE
FT	MISURATORE PORTATA
M	MOTORE

Autorità d'ambito Torinese 3

Autorità d'ambito Torinese A.T.O.3

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PROG. N° -

PROGETTO DEFINITIVO

Comuni di Collegno

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RECUPERO TERMICO

OPERE IMPIANTISTICHE

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il Direttore Generale

Dott. Ing. Marco Acri

REV.	DESCRIZIONE	DATA	REDAZIONE	VERIFICA	APPROVAZIONE
3					
2					
1					
0	EMISSIONE	MARZO 2016	TROIANO	VAUDANO	VAUDANO

documento n°: 07

Progettista: Ing. Giorgio VAUDANO
Ing. Ugo FAUSONE

Collaboratore : P.ind. Marco TROIANO

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Risorse Idriche

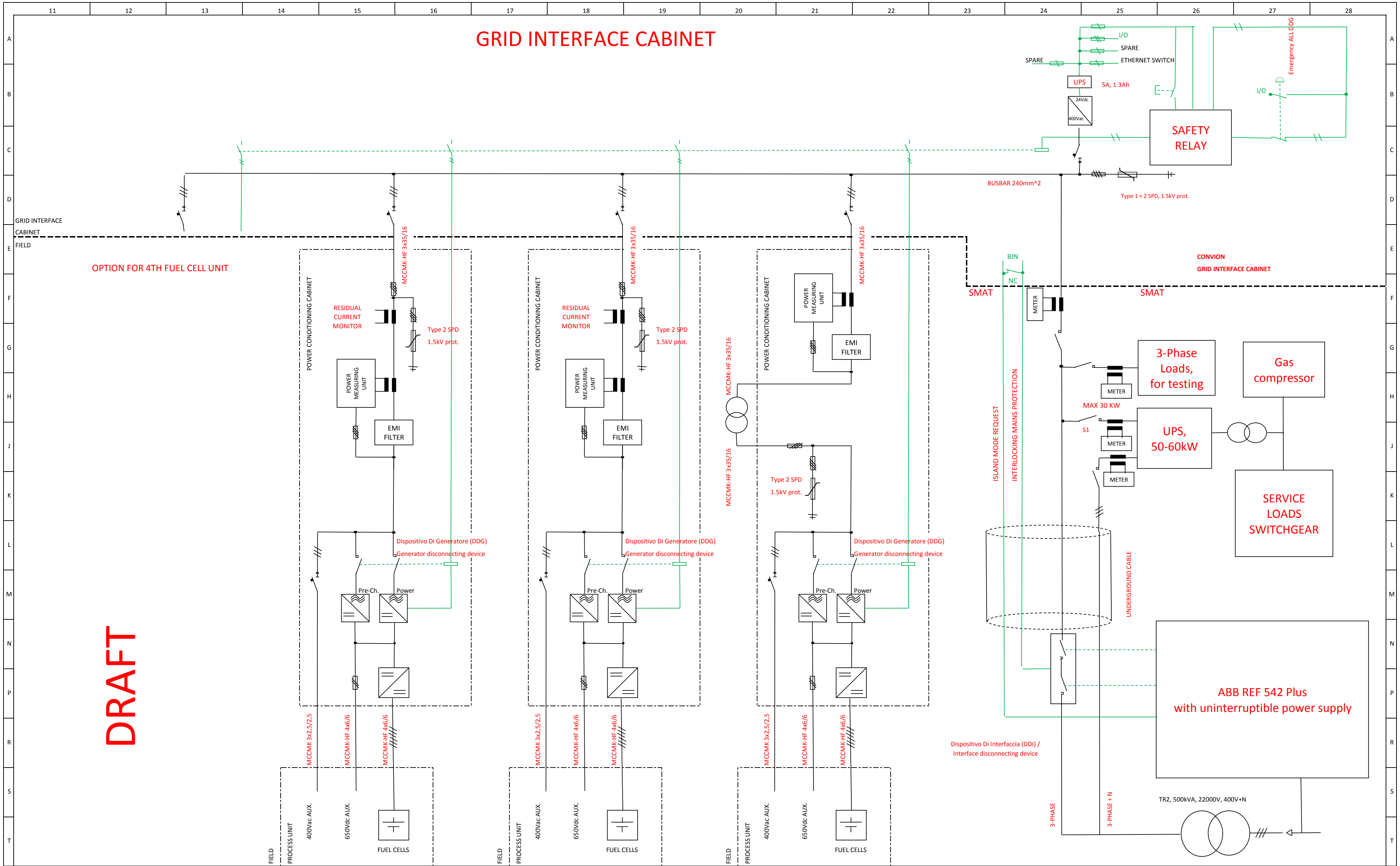
file:

PROGETTO	ID R.I.	documento
- -	RI0411	SOFC-DEF-03

PRGMO0012/G

7.6 **Appendix F – "**ELECTRIC LAYOUT

GRID INTERFACE CABINET



REV: CHANGE DESCRIPTION	REV BY/DATE

DESIGNED BY	DRAWN BY	CHECKED BY	APPROVED BY	DRAWING TYPE	PROJECT	DRAWING NO.	PAGE	REVISION
MLI / 10.3.2016	MLI / 10.3.2016				FC50 2.0			

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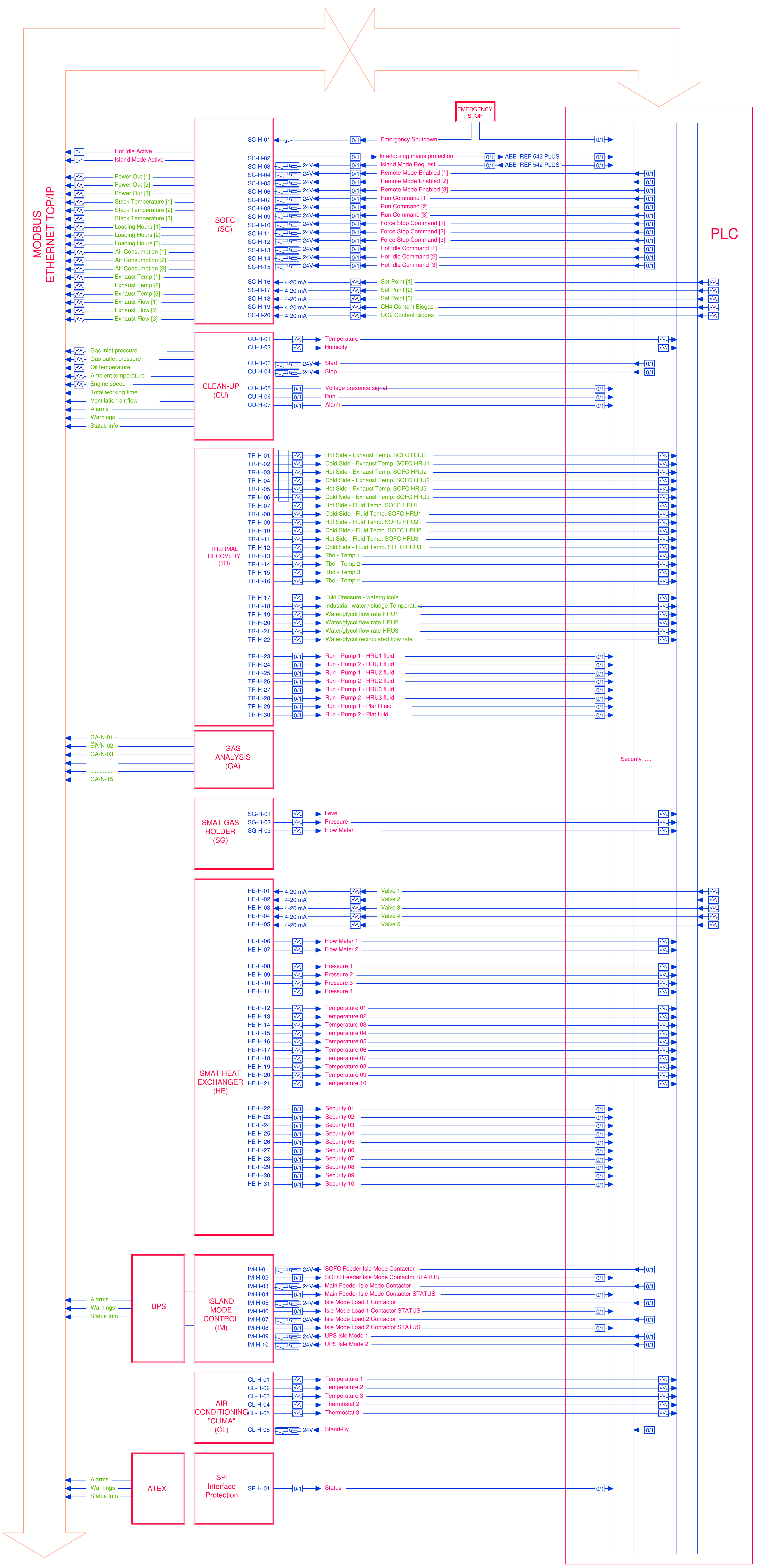
NAME
CONVION OY
SMAT ONE-LINE DIAGRAM
CIRCUIT DIAGRAM

7.7 **Appendix G –** "SEGNALI DI COMUNICAZIONE CON PLC"



Autorità d'ambito Torinese 3

Autorità d'ambito Torinese A.T.O.3

smat gruppo

PROG. N° — PROGETTO ESECUTIVO

Comune di

Collegno

PROGETTO DEMOSOFC

SEGNALI DI COMUNICAZIONE CON PLC

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il Direttore Generale
Dott. Ing. Marco Acri

REV.	DESCRIZIONE	DATA	REDAZIONE	VERIFICA	APPROVAZIONE
3					
2					
1					
0	Emissione	Marzo 2016	MENSA	VAUDANO	VAUDANO

documento n°: EL.03

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PROGETTO	ID R.I.	documento
	RI0411	file: SOFC-ESE-b01.dwg

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PRGMO0012/F