DEMOSOFC

FCH2-JU PROJECT

DEMOSOFC

Project n° 671470

“DEMOnstration of large SOFC system fed with biogas from WWTP”

Deliverable number 6.2

DEMOSOFC Value chain analysis

(Task leader: Imperial College London - Participants: POLITO, CONVION, SMAT, VTT - Start: M48 - End: M60)

Due Date of Delivery:	M60
Actual Submission Date:	30.09.2020
Lead Beneficiary:	Imperial College London
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Work package:	WP6
Estimated PM:	10
Dissemination Level:	Public
Nature:	R
Version:	1
Total number of pages:	110

Abstract:

This report presents a bottom-up cost assessment of a DEMOSOFC system, composed by the wastewater treatment plant preparation and retrofitting, the installation of a biogas cleaning system and SOFC system, and the operating and maintenance costs for a DEMOSOFC project. The total cost and levelized cost of energy (LCOE) was calculated for a range of scenarios corresponding to different SOFC production rates and stack replacements. Results showed that 100 kW DEMOSOFC plants could obtain a LCOE ranging from 0.068-0.134 €/kWh, while 250 kW projects could obtain a LCOE between 0.064 and 0.127 €/kWh.

An assessment of the value added by a DEMOSOFC project at different stages of its supply chain is presented. Different activities that added/captured value from this project included labour from manufacturing companies and local companies performing O&M; the margin for manufacturers of the SOFC and other equipment; security of energy supply captured by the WWTP by enhancing energy self-sufficiency and stable energy costs; and lower air pollution levels captured by end-users and workers of the DEMOSOFC plant.

Keyword list: biogas, biogas exploitation, SOFC, value chain analysis, levelized cost of energy.

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1. Introduction

The DEMOSOFC project aims to demonstrate a distributed combined heat and power (CHP) solid oxide fuel cell (SOFC) system fed by biogenous CO2 neutral fuel, coupled to a wastewater treatment plant (WWTP). The biogas fuel is extracted from the anaerobic digestion of municipal wastewater from the WWTP, and feeds into SOFC units which in turn provide heat and power to the WWTP.

The DEMOSOFC project was implemented in Collegno WWTP (Turin, Italy), a municipal sewage treatment plant owned by SMAT (Società Metropolitana Acque Torino). This plant has a nominal capacity of 250,000 Person Equivalent (P.E.), and currently serves around 185,000 P.E. The DEMOSOFC consisted in retrofitting the existing plant with a biogas cleaning and compression section, three 58 kWe SOFC units, and a heat recovery system in order to serve the plant's heating and power needs [1].

This report delivers an analysis of the supply chain costs for a system of this kind, considering the costs of retrofitting a WWTP, installing the SOFC, operating the whole system, and the auxiliary activities needed to operate it. It aims to calculate a levelized cost of energy for the life cycle of a DEMOSOFC project, and compare these results against alternative technologies to supply WWTP energy needs.

1.1 Aims

The aims of this report are to:

- Deliver a bottom-up assessment of the value added in manufacturing activities, installation, and operation of DEMOSOFC plants.
- Calculate the levelized cost of energy for a DEMOSOFC plant, in a number of scenarios, and compare them with other alternatives for energy provision.

2. Description of DEMOSOFC system

This section describes the initial Collegno WWTP, and the retrofitting that needed to be carried out in order to install the SOFC system. This report will start from the description of this particular case study in order to identify the main actions, carried out works, and installed equipment required to retrofit a generic WWTP. These will be the basis for the value chain analysis of the DEMOSOFC system.

2.1 Initial installation

As previously described, the DEMOSOFC project was implemented in Collegno WWTP for municipal sewage treatment. The plant initially counted with an anaerobic digestor that produced biogas from sewage sludge. The produced biogas was initially being combusted in a gas boiler for pre-heating the sludge entering the digester. The excess biogas produced was being flared [1].

The retrofitting and energy efficiency actions proposed in this project were:

1) The installation of three 58 kW SOFC CHP units for using onsite produced biogas to serve heat and electricity demands. The 3 modules are specified to provide around 25-30% if the WWTP electricity demands, and most of the plant's heat demands [1].
2) Installation of a biogas cleaning and compression system, for biogas to be used in the SOFC units.
3) Installation of a heat recovery loop, in order to recover thermal energy from exhaust gases and use it to preheat the sludge entering the digestor.

2.2 DEMOSOFC retrofitting

The DEMOSOFC retrofitting project involved the installation of three C50 SOFC modules provided by the company Convion [2]. At present, two C50 modules have been installed, while the third one remains to be installed during 2020 [3]. Each module is fed by biogas produced in the WWTP. In order to avoid degradation of the fuel cells, the biogas produced in the biodigester needs to be further cleaned [4]. As stated previously, the system's retrofit consisted of three components, the SOFC modules, a biogas system cleaning unit, and a thermal recovery system, briefly described in the following sections.

The retrofits involve a series of civil, mechanical, and electrical works to incorporate the new components, additionally to the equipment. The retrofitted plant is schematised in Figure 1.

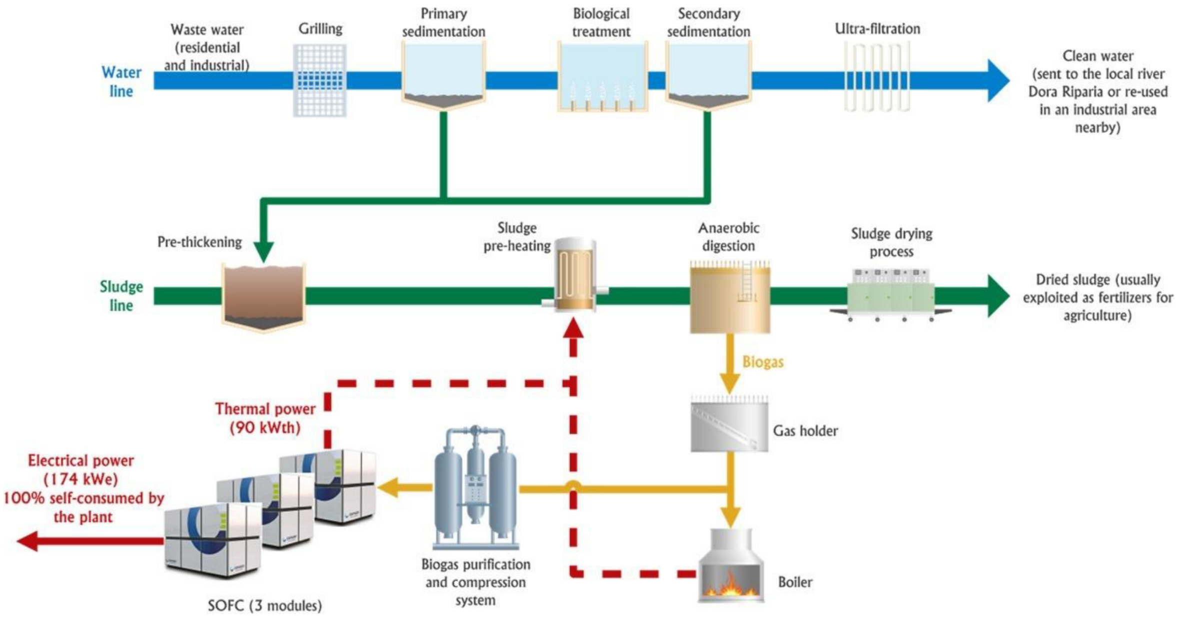

Figure 1: Process diagram retrofitted scenario[1].

2.2.1 SOFC modules

The plant was designed to install three C50 SOFC modules of 58 kWe. Each module can work autonomously. The SOFCs require that the input biogas complies with the following characteristics:

- Max sulphur content: <30 ppb
- Siloxanes: < 10 ppb
- Halogen compounds: <1 ppm
- Allowed level of humidity: Non-condensing

The main specifications of Convion's C50 modules are shown in Table 1.

Table 1: Convion C50 module general parameters [2]

Performance	Targets
Net power output	58 kW (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	
NO_x	<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 (Lx W x H)	
Power unit	3.5 x 1.9 x 2.3m
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

2.2.2 Biogas cleaning and compression system

The cleaning unit extracts biogas from the digester, compresses, dehumidifies, and cleans it from contaminants (sulphur, siloxanes, halogens, etc. [5]), in order to comply with the described input fuel requirements. Figure 2 shows the cleaning system components.

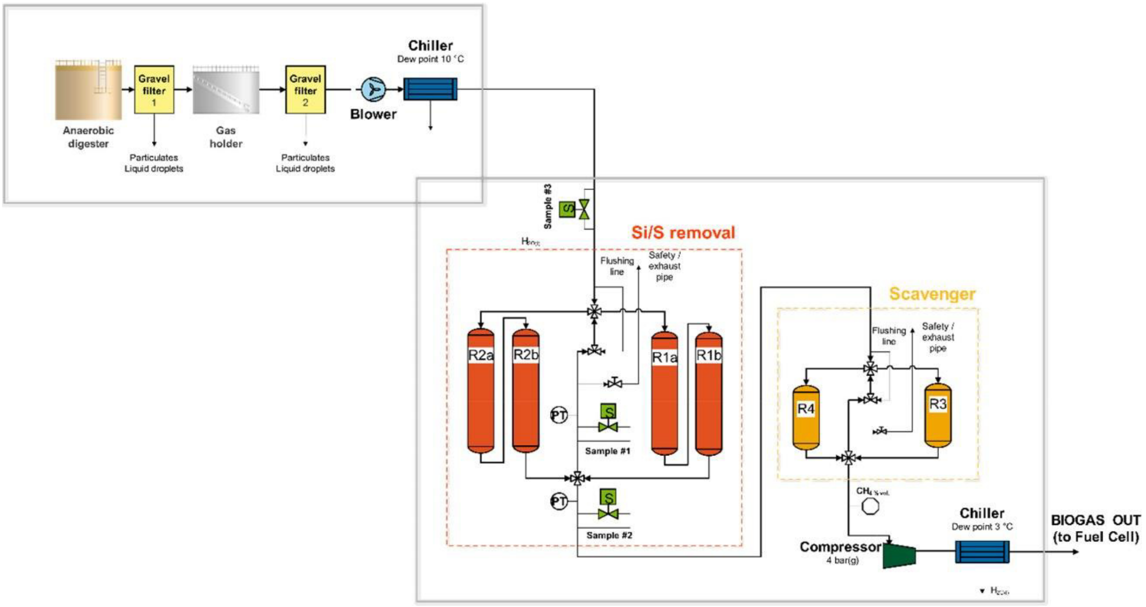

Figure 2: Cleaning system components [1].

2.2.3 Thermal recovery system

Heat from the SOFC exhaust gas is recovered in a gas-water/glycol heat exchanger placed inside each module and connected to a central pipeline. The pipeline transports the fluid (30% glycol in water) to a secondary water/glycol-sludge heat exchanger used to preheat the sludges entering the digester. The system components include the pipelines, heat exchangers, pumps, civil works, and ancillary equipment. Figure 3 shows the heat recovery system diagram.

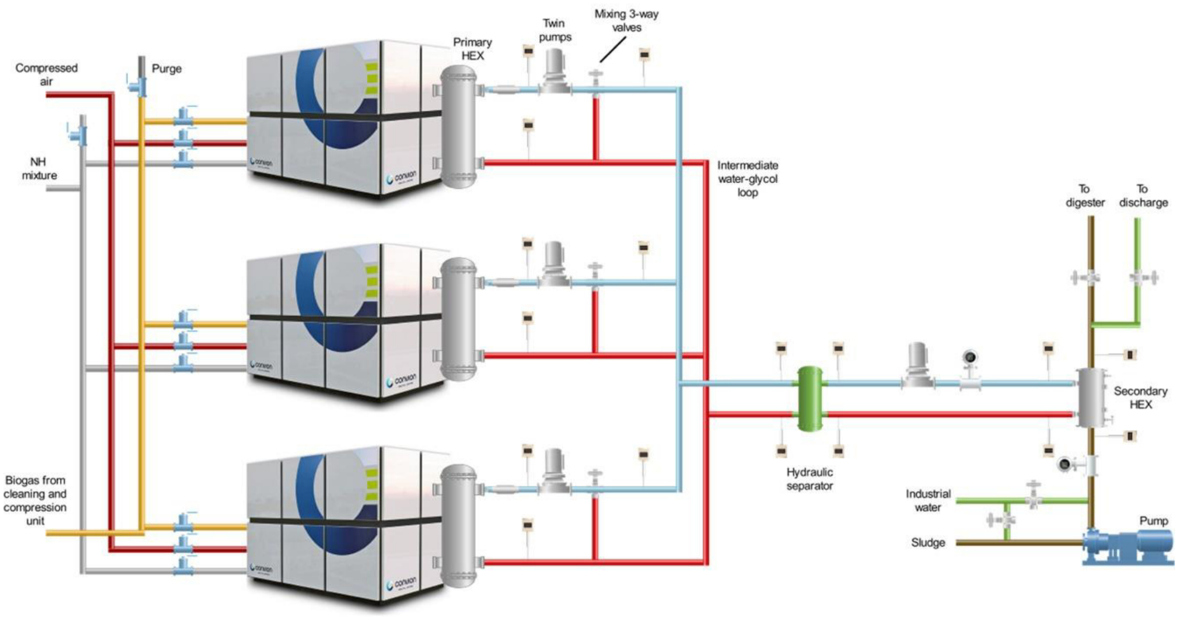

Figure 3: Thermal recovery system [1].

3. DEMOSOFC cost breakdown

This section presents the cost analysis of a whole DEMOSOFC system cost. The system's cost assumes there is a WWTP which is retrofitted to include SOFC CHP units, together with the required biogas cleaning system and thermal recovery system. The cost analysis is divided into three main components: The site preparation, which includes the cleaning and heat recovery systems' capital costs; the capital cost of SOFC units; and the operating and maintenance costs of the whole system. Each of these will be further disaggregated to understand the cost components of the incumbent supply chain.

3.1 Site preparation capital costs

The site preparation capital costs consist of the works performed to prepare the site to install the DEMOSOFC system, and they are divided into mechanical works, electrical works, civil works, clean-up system, and auxiliary works. Three costs are given here: the initial estimate of the capital costs, the actual cost of the DEMOSOFC system, and an optimised cost. The optimised cost was obtained in a posterior design optimisation, in order to represent better estimates of a standard retrofit project to any generic plant, as pilot projects such as the DEMOSOFC are more expensive due to learning curves. The optimised costs were obtained from [6], which is embedded in the Appendix.

3.1.1 Mechanical works

The mechanical works consist of the installation of the pipeline systems in the DEMOSOFC project. This includes mechanical works for the biogas cleaning system and for the thermal recovery system. The mechanical works include:

- Biogas pipelines: pipes, valves, measurement equipment, chillers, blowers.
- Heat recovery pipelines: pipes (primary and secondary), valves, measurement equipment, and pumps.
- Air compression pipeline: pipes, filters, storage tank, and chiller.

Table 2 shows the mechanical works components with the initial estimated costs for the DEMOSOFC plant, the actual cost, and the optimised design cost.

Table 2: Mechanical works costs [6]

Item	Estimated Cost [€]	Unitary cost (estimated) [€/kW]	Actual Cost [€]	Unitary cost (actual) [€/kW]	Optimised Cost [€]	Unitary cost (optimised) [€/kW]
Primary heat recovery loop	36,370	209	32,530	187	17,610	101
Secondary heat recovery line	56,010	322	51,480	296	0	0
Sludge warming line	24,680	142	27,520	158	0	0
Heating of technical water line	5,020	29	3,400	20	0	0
Compressed air line	4,840	28	4,840	28	4,010	23
Cost of labour	57,060	328	60,990	351	24,840	143
Biogas and technical gases line	72,020	414	62,190	357	43,390	249
Additional works	29,730	171	20,490	118	7,400	43
Safety cost	3,670	21	6,500	37	5,150	30
Total	**289,400**	**1,663**	**269,940**	**1,551**	**102,400**	**589**

Figure 4 shows these cost components graphically. The bars represent the actual DEMOSOFC costs. The upper error bars represent the initial cost estimates, while the lower error bars show the costs or the optimised plant design.

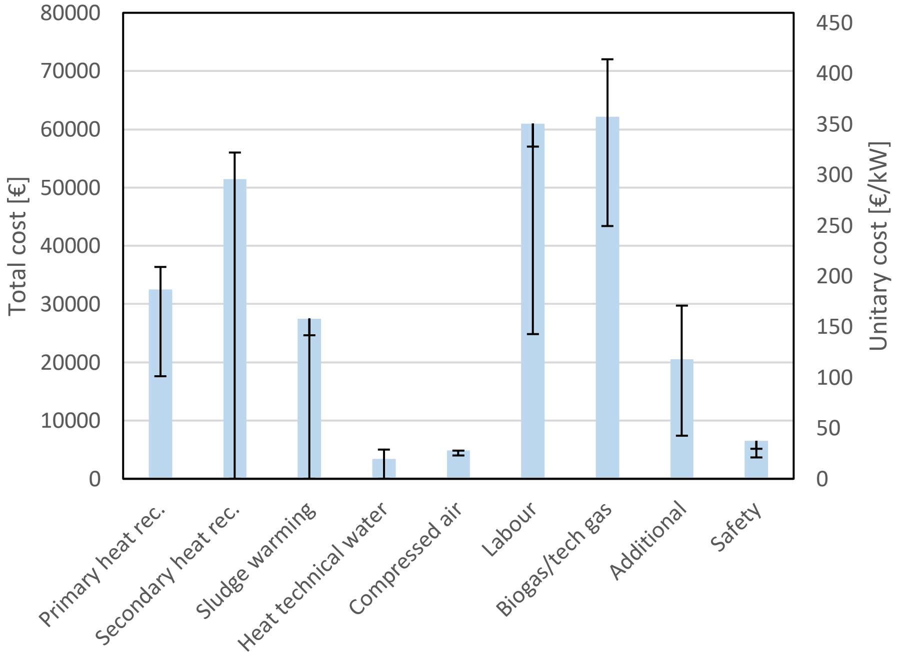

Figure 4: Mechanical total and unitary costs. Bars: Actual DEMOSOFC cost. Upper error bars: Initial cost estimates. Lower error bars: Optimised cost estimates.

3.1.2 Electrical works

The electrical works consider ground ducts, cable installations in the duct, and all electrical connections required by the DEMOSOFC system, including electrical connections to the SOFC units and clean-up system, control systems, measuring instruments, uninterruptible power supply (UPS), the SOFC modules interface, and the installation of the electrical cabinet in the technical building. For the electrical works, there was no breakdown of the actual cost, only a total value, as shown in Table 3.

Table 3: Electrical works costs [6]

Item	Estimated Cost [€]	Unitary cost (estimated) [€/kW]	Actual Cost [€]	Unitary cost (actual) [€/kW]	Optimised Cost [€]	Unitary cost (optimised) [€/kW]
Main ground duct	26,410	152			0	0
Secondary ground duct	1,260	7			0	0
Electrical cabinet	47,790	275			50,270	289
CONVION interface cabinet	630	4			0	0
SOFCs electric connections	630	4			4,354	25
Clean-up system electric connections	1,260	7			2,094	12
Programmable Logic Control (PLC)	45,270	260			58,364	335
Optical fibre	2,520	14			0	0
Total	**125,770**	**723**	**173,910**	**999**	**115,082**	**661**

Figure 5 shows the electrical cost components. The bar shows the actual total DEMOSOFC electrical costs. There was no cost breakdown for the actual DEMOSOFC electrical costs, therefore only the initial estimates and optimised costs were broken down into cost components in this figure. The upper error bars represent the initial cost estimates, while the lower error bars show the costs or the optimised plant design.

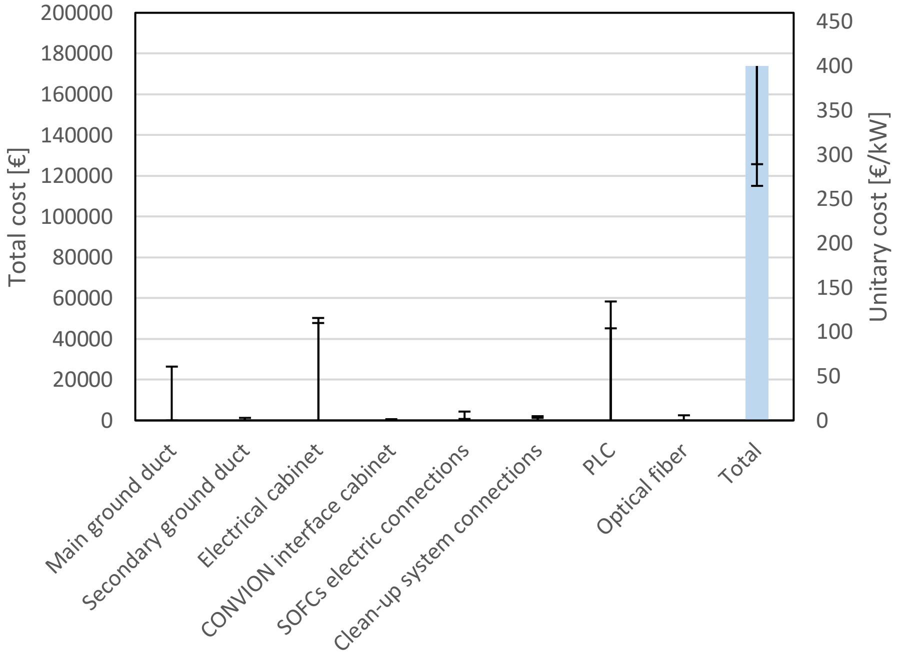

Figure 5: Electrical total and unitary costs. Bar: Actual total DEMOSOFC cost. Upper error bars: Initial cost estimates. Lower error bars: Optimised cost estimates.

3.1.3 Civil works

Civil works refer to the concrete bases, pipe racks and building infrastructure needed to adapt a WWTP as the DEMOSOFC project. They consist broadly of a reinforced concrete basement where cable ducts pass, pipe racks connecting biogas storage and the SOFC modules, and the technical building where the control room stands. Table 4 shows the costs of civil works of the items within each structure.

Table 4: Civil works costs [6]

Structure	Item	Estimated cost [€]	Unitary cost (estimated) [€/kW]	Actual Cost [€]	Unitary cost (actual) [€/kW]	Optimised Cost [€]	Unitary cost (optimised) [€/kW]
Basement and technical building	Excavation and ground moving	8,340	48	16,450	95	2,345	13
	Demolition and removal	16,560	95	12,940	74	-	-
	Reinforced concrete works	41,940	241	68,770	395	12,472	72
	Metal framing works	17,790	102	33,210	191	4,305	25
	Ducts, covers, and floors	12,940	74	34,130	196	11,213	64
	Frames and external cladding	31,160	179	47,640	274	-	-
Pipe rack	Excavation and ground moving	330	2	5,520	32	52	0
	Demolition and removal	800	5	7,670	44	-	-
	Reinforced concrete works	5,060	29	6,790	39	776	4
	Metal framing works	41,410	238	51,710	297	2,646	15
	Ducts, covers, and floors	-	-	990	6	-	-
Safety				5,687	33	1,782	10
Total		**176,330**	**1,013**	**291,507**	**1,675**	**35,591**	**205**

Figure 6 shows the civil works cost components. The bars represent the actual DEMOSOFC costs. The upper error bars represent the initial cost estimates, while the lower error bars show the costs or the optimised plant design.

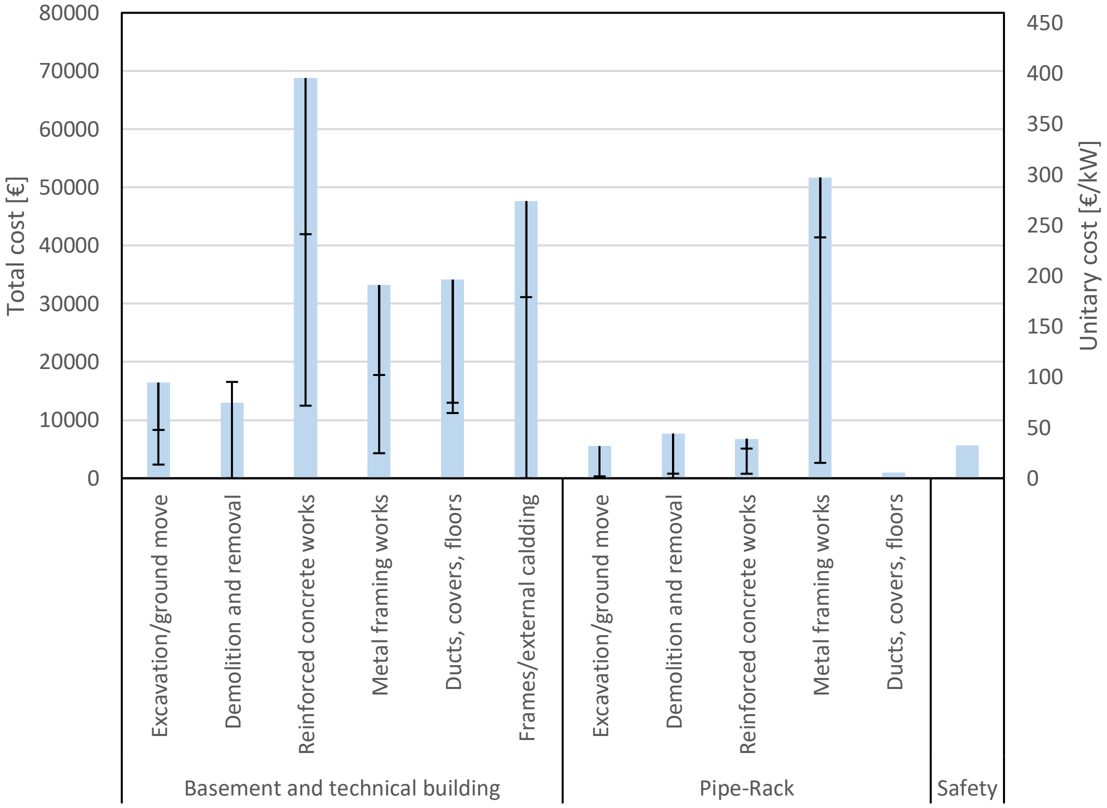

Figure 6: Civil total and unitary costs. Bars: Actual DEMOSOFC cost. Upper error bars: Initial cost estimates. Lower error bars: Optimised cost estimates.

3.1.4 Clean-up system

The clean-up system consists on the gas recovery station, the biogas treatment system, and the initial filters. For the clean-up works, there was no breakdown of the actual cost, only a total value, as shown in Table 5.

Table 5:Clean-up system costs [6]

Item	**Estimated Cost [€]**	**Unitary cost (estimated) [€/kW]**	**Actual Cost [€]**	**Unitary cost (actual) [€/kW]**	**Optimised Cost [€]**	**Unitary cost (optimised) [€/kW]**
Gas recovery station	36,710	211			5,306	30
Biogas treatment system	159,810	918			115,407	663
First activated siloxane carbon filter	4,320	25			1,327	8
First activated sulphur carbon filter	4,320	25			1,327	8
Technical assistance	8,640	50			6,633	38
Transportation costs	2,160	12			2,653	15
Total	**215,960**	**1,241**	**221,087**	**1,271**	**132,652**	**762**

Figure 7 shows the clean-up system cost components. The bar shows the actual total DEMOSOFC costs. No cost breakdown was available for actual clean-up costs, therefore only the initial estimates and the optimised costs were broken down in this figure. The upper error bars represent the initial cost estimates, and the lower error bars show the costs or the optimised plant design.

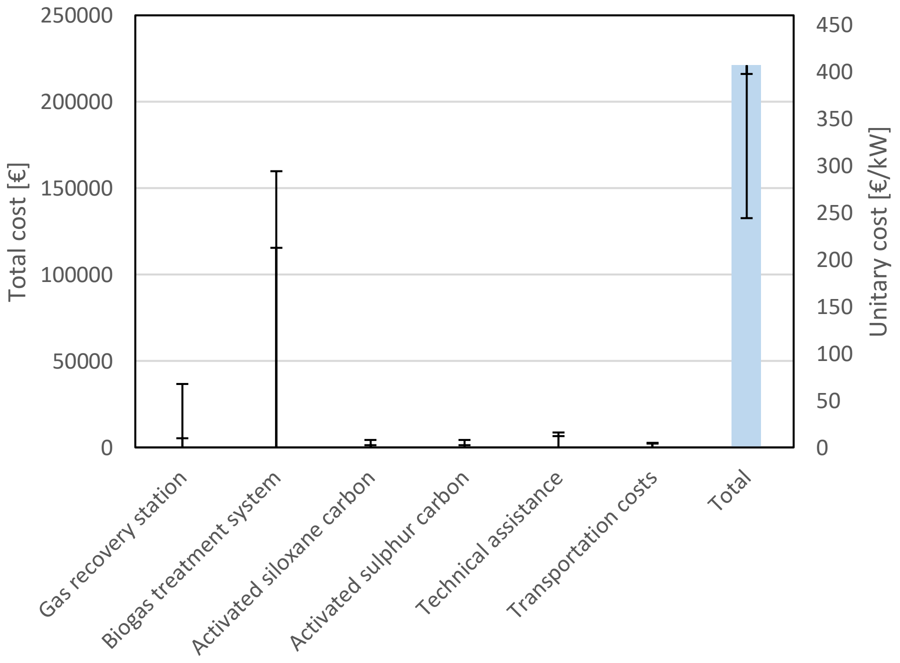

Figure 7: Clean-up total and unitary costs. Bar: Actual total DEMOSOFC cost. Upper error bars: Initial cost estimates. Lower error bars: Optimised cost estimates.

3.1.5 Auxiliary works

Table 6 shows the auxiliary works costs.

Table 6: Auxiliary works costs [6]

Item	Estimated Cost [€]	Unitary cost (estimated) [€/kW]	Actual Cost [€]	Unitary cost (actual) [€/kW]	Optimised Cost [€]	Unitary cost (optimised) [€/kW]
Gas analyser	53,290	306	59,000	339	31,000	178
Connection to electrical grid	2,500	14	2,960	17	2,960	17
Technical gas	22,480	129	24,260	139	15,178	87
Unloading and positioning	5,000	29	5,460	31	5,460	31
Total	**83,270**	**479**	**91,680**	**527**	**54,598**	**314**

Figure 8 shows the cost components. As in previous figures, the bars represent the actual DEMOSOFC costs, the upper error bars represent the initial cost estimates, and the lower error bars show the costs or the optimised plant design.

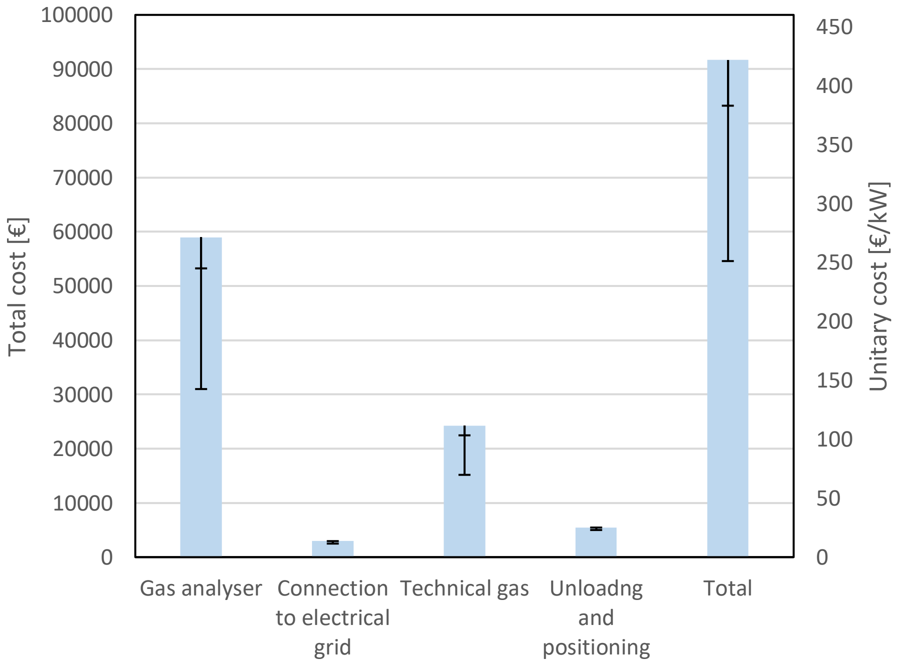

Figure 8: Auxiliary total and unitary costs. Bars: Actual DEMOSOFC cost. Upper error bars: Initial cost estimates. Lower error bars: Optimised cost estimates.

3.1.6 Site preparation cost summary

Figure 9 and Figure 10 show the cost summary for the site preparation costs, as total costs and unitary cost, respectively.

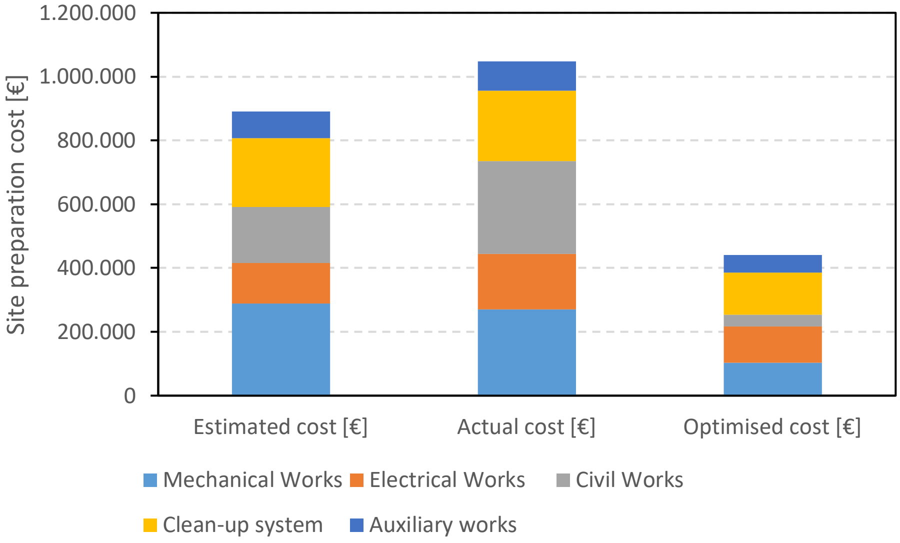

Figure 9: Site preparation cost breakdown

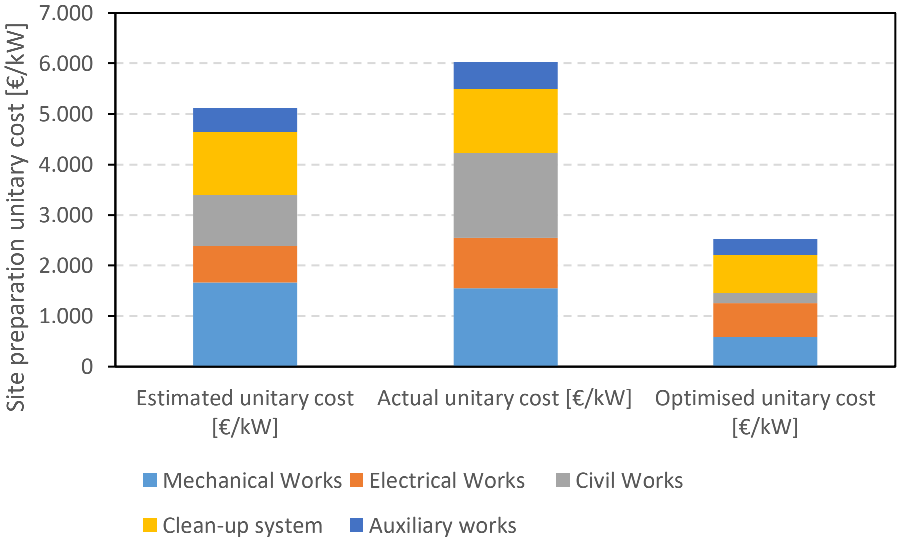

Figure 10: Site preparation unitary cost breakdown

3.2 SOFC system capital costs

This section presents the manufacturing costs for SOFC systems. SOFC systems include multiple fuel cell stacks and balance of plant (BOP) components, which include the fuel processor, support hardware, fuel and air supply, controls and sensors, and electrical equipment [7, 8]. Each fuel cell stack consists of 2 end plates and repeat units. Repeat units include one interconnect and anode frame, once cell and picture frame, one cathode frame, one cathode and one anode mesh, and seals between frames, the cell, and interconnect [8].

Figure 11 shows the materials, components, and subsystems that compose a SOFC system. The figure shows the critical components and subsystems, where criticality is assessed based on performance, cost, technical evolution, supplier base, new market, and socioeconomic impact [7].

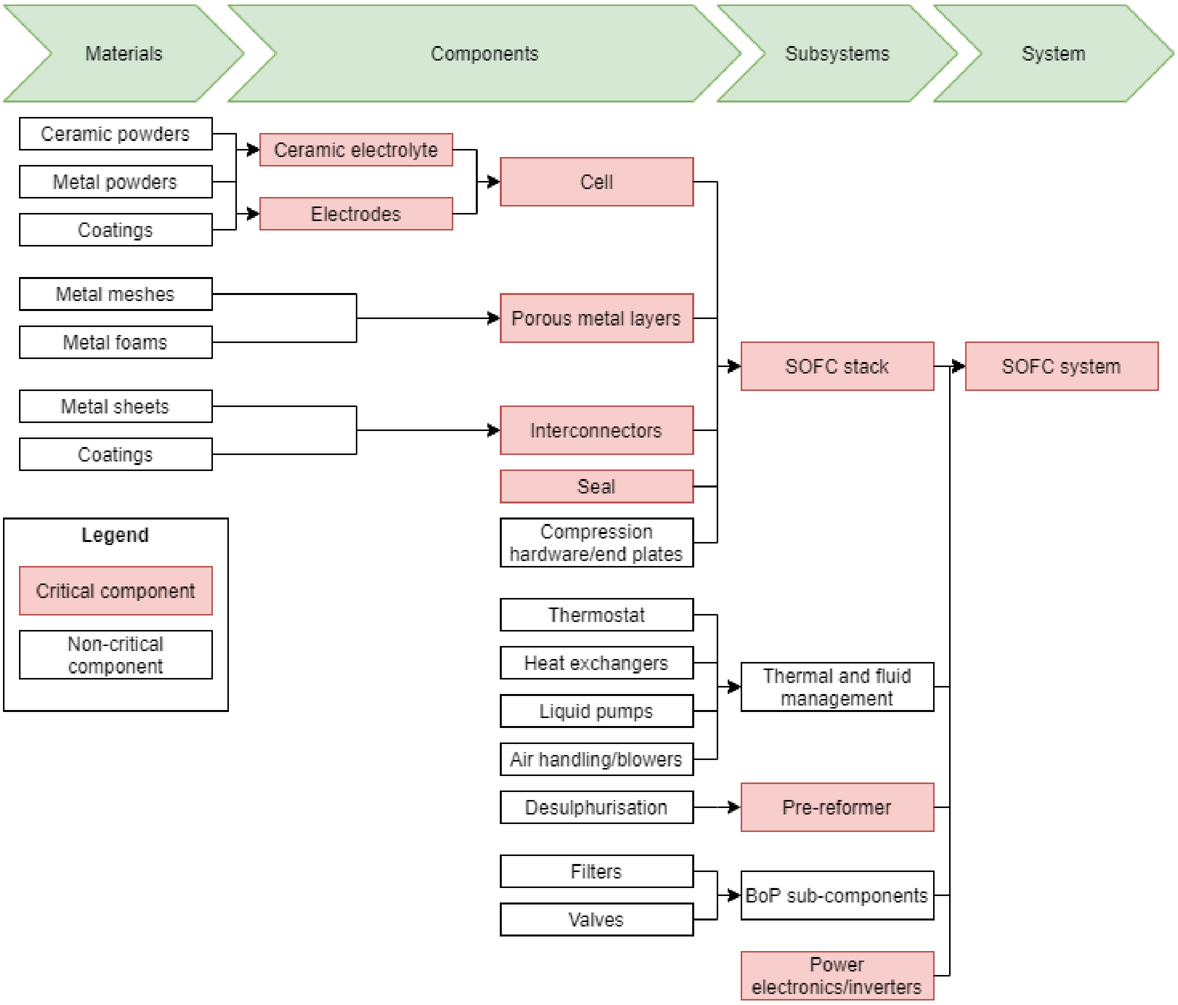

Figure 11: SOFC systems and critical components [7].

The cost of manufacturing will be disaggregated into SOFC main component costs and added value, for both a 100 kW and a 250 kW fuel cell system. Some general design parameters are presented in Table 7.

Table 7: 100 kW and 250 kW fuel cell general design parameters [8].

Parameter	100 kW	250 kW
Cell power density (W/cm^2)	0.28	
Cell current density (A/cm^2)	0.4	
Cell voltage (VDC)	0.7	
Active area per cell (cm^2)	414	
System net power (kW, continuous)	100	250
System gross power (kW, continuous)	120	300
Number and size of stacks per system	4 x 30 kW (gross)	10 x 30 kW (gross)
Number of cells	259	259
Stack open circuit voltage (VDC)	285	285
Full load stack voltage (VDC)	181	181

The SOFC stack represents the highest cost component within a SOFC system. The cost components within each stack are detailed in Table 8, according to annual production rates.

Table 8: SOFC stack cost components [8].

	30 kW Stack - 100 kW System				**30 kW Stack - 250 kW System**			
Production volume (units/year)	**100**	**1000**	**10000**	**50000**	**100**	**1000**	**10000**	**50000**
Ceramic cells	€4,084	€2,989	€2,706	€2,675	€3,365	€2,777	€2,679	€2,669
Interconnects	€849	€525	€356	€355	€733	€410	€359	€353
Anode frame	€323	€306	€300	€300	€313	€307	€300	€299
Anode mesh	€259	€184	€158	€158	€231	€160	€158	€158
Cathode frame	€113	€98	€94	€93	€104	€98	€94	€93
Cathode mesh	€262	€187	€160	€160	€234	€162	€160	€160
Picture frame	€128	€108	€104	€104	€117	€109	€104	€103
Laser weld	€305	€72	€72	€72	€122	€72	€72	€72
Glass ceramic sealing	€1,114	€479	€434	€431	€638	€449	€431	€431
End plates	€761	€690	€632	€630	€755	€657	€630	€630
Assembly hardware	€178	€166	€156	€149	€173	€162	€152	€145
Assembly labour	€172	€162	€161	€161	€165	€161	€161	€161
Stack brazing	€70	€67	€48	€43	€69	€58	€43	€43
Test and conditioning	€1,169	€645	€592	€589	€808	€606	€590	€588
Total cost per stack	**€9,786**	**€6,680**	**€5,973**	**€5,918**	**€7,827**	**€6,188**	**€5,933**	**€5,905**

Table 9 shows the cost of manufacturing each stack and the total SOFC assembly cost, considering the total number of stacks within 100 kW and 250 kW systems for different annual production rates.

Table 9: SOFC stack manufacture cost summary [8]

	30 kW Stack - 100 kW System				**30 kW Stack - 250 kW System**			
Production rate (units/year)	**100**	**1000**	**10000**	**50000**	**100**	**1000**	**10000**	**50000**
Material	€3,316	€2,979	€2,909	€2,898	€3,145	€2,920	€2,903	€2,893
Labour	€1,673	€1,656	€1,654	€1,654	€1,662	€1,655	€1,654	€1,654
Machine	€3,890	€1,429	€846	€808	€2,293	€1,033	€816	€801
Scrap	€685	€465	€413	€409	€546	€428	€410	€408
Tooling	€222	€151	€150	€150	€180	€152	€150	€150
Part total	€9,786	€6,680	€5,973	€5,918	€7,827	€6,188	€5,933	€5,905
Number per system	4	4	4	4	10	10	10	10
Total system cost	**€39,146**	**€26,720**	**€23,890**	**€23,673**	**€78,267**	**€61,879**	**€59,328**	**€59,045**

As described in Figure 11, a SOFC system is composed by SOFC stacks, thermal and fluid management components, BOP components, and power electronics components. Table 10 shows the cost disaggregation of all these, the cost of assembling them, and the sales margin, for 100 kW and 250 kW systems and different production rate scenarios. The table also shows the costs of installing the system.

Table 10: Cost summary for 100 and 250 kW units based on annual production rates [8], and installation costs.

Description	**100 kW units/year**				**250 kW units/year**			
	100	**1000**	**10000**	**50000**	**100**	**1000**	**10000**	**50000**
Total stack manufacturing	€41,444	€27,524	€24,542	€24,315	€81,540	€63,267	€60,589	€60,297
Fuel and air supply components	€8,693	€7,143	€6,420	€5,982	€15,736	€13,502	€12,306	€11,658
Fuel processor components	€7,091	€4,896	€4,512	€4,267	€12,338	€8,425	€7,399	€7,098
Heat recovery components	€18,109	€16,940	€15,850	€15,154	€29,117	€27,277	€25,557	€24,484
Power electronic, control, and instrumentation components	€45,570	€37,519	€30,635	€25,983	€101,447	€81,743	€64,890	€53,507
Assembly components and additional work estimate	€9,550	€8,669	€7,787	€7,031	€16,435	€14,973	€13,511	€12,195
Total system cost, pre-markup	€130,457	€102,693	€89,744	€82,732	€256,615	€209,187	€184,250	€169,239
System cost per KW$_{net}$, pre-markup	€1,305	€1,027	€897	€827	€1,026	€837	€737	€677
Sales markup	50%	50%	50%	50%	50%	50%	50%	50%
Total system cost, with markup	€195,685	€154,039	€134,618	€124,098	€384,921	€313,780	€276,376	€253,858
System cost per KW$_{net}$, with markup	€1,957	€1,540	€1,346	€1,241	€1,540	€1,255	€1,106	€1,015
Installation cost	€53,750	€43,000	€38,700	€34,400	€53,750	€43,000	€38,700	€34,400

The contribution of each component towards the total system's costs are shown in a unitary base (cost/kW) in Figure 12.

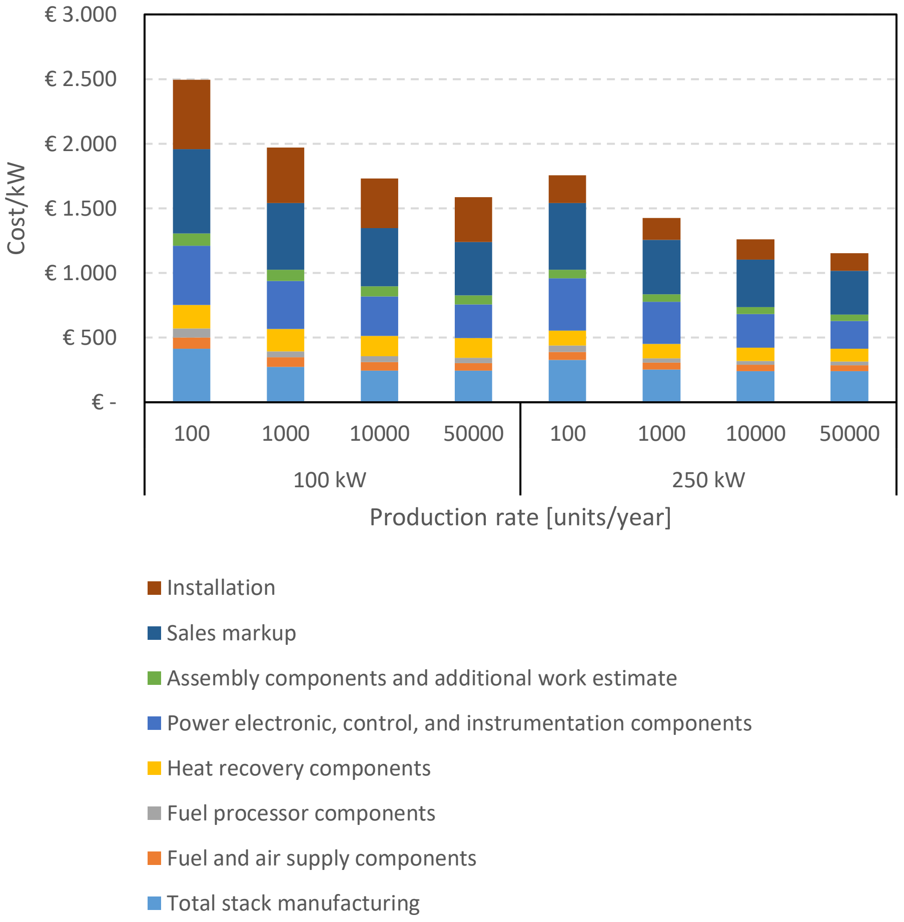

Figure 12: Disaggregated unitary costs of 100 kW and 250 kW SOFC systems for different production rates

3.3 System operating and maintenance costs

3.3.1 Clean-up system

As previously stated, the DEMOSOFC project is a pilot project. Therefore, it is oversized, and with safety standards that are above normal. This section will present the operation and maintenance costs of this oversized system and provide an estimate for the costs of an optimised one, based on the gained experience. Firstly, the operation and maintenance costs of the actual pilot plant will be presented, followed by an estimation of a scaled-down optimised system.

Pilot plant current scenario

The pilot plant clean-up system (Biokomp unit) includes 2 chillers, 1 blower, and 1 compressor, inside an insulated and ventilated container. It also has 6 vessels with 250-300 kg of siloxane and sulphur removal sorbents each. The maintenance work is planned to occur every 6000 hrs. The following section assumes the Biokomp units operates at a capacity factor of 0.957, which is equivalent to 8383 hrs/year. Thus, in the years 3, 6, 8, 11, and 13, there are two maintenance works in a year. Table 11 shows the parameters used to calculate yearly sorbent costs for the cleaning up plant. As shown in the table, it is assumed that 2 vessels are replaced per year: one for sulphur and one for siloxane removal. Sorbent disposal costs include labour, transport, lifting and other equipment rental, and sorbent disposal bags and materials.

Table 11: Yearly sorbent replacement costs- current values

Number of vessels	6	
Number of vessels replaced per year	2	
Sorbents per vessel	250	kg
Total sorbent requirement	500	
Sorbent costs	5	€/kg
Labour	Assumed 10%	% of total cost
Cost for AC replacement	2,750	€
Sorbent disposal costs	8,885	€
Total yearly cost	**11,635**	**€**

Table 12 shows the parameters used to calculate costs of electricity consumption from the compressor, biogas blower, and chillers, and Table 13 shows the yearly total operation and maintenance costs for the cleaning-up system.

Table 12: Electricity cost blower, chillers, compressor- actual values

	Nominal power	
Compressor	4	kW
Biogas blower	0.6	kW
Chillers	5	kW
Total	9.6	kW
	Electricity consumption	
Capacity factor	0.957	
Yearly consumption	80480	kWh
Electricity cost (SMAT)	0.16 [9]	€/kWh
Yearly electricity cost	**12,877**	**€/y**

Table 13:Yearly operation and maintenance cleaning-up pilot plant costs

Activity	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Cleaning internal compressor	-	-	-	-	-	-	-	-	-	-	500	-	-	-	-
Cleaning internal electrical box	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Clean oil cooler	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Replace refiltration panel 1	41	41	82	41	41	82	41	82	41	41	82	41	82	41	41
Replace refiltration panel 2	52	52	103	52	52	103	52	103	52	52	103	52	103	52	52
Change oil	354	354	708	354	354	708	354	708	354	354	708	354	708	354	354
Replace oil filter cartridge	41	41	83	41	41	83	41	83	41	41	83	41	83	41	41
Replace gas/oil separator filter cartridge	63	63	126	63	63	126	63	126	63	63	126	63	126	63	63
Replace aspiration filter cartridge	706	706	1,411	706	706	1,411	706	1,411	706	706	1,411	706	1,411	706	706
Replace coalescent filter before dryer	353	353	706	353	353	706	353	706	353	353	706	353	706	353	353
Replace coalescent filter after dryer	394	394	789	394	394	789	394	789	394	394	789	394	789	394	394
Replace thermostatic valve kit	-	61	61	-	61	-	-	61	61	-	61	-	61	-	61
Replace minimum pressure valve kit	-	28	28	-	28	-	-	28	28	-	28	-	28	-	28
Replace oil cover visor	-	35	35	-	35	-	-	35	35	-	35	-	35	-	35
Replace elastic element	-	-	15	-	-	15	-	-	15	-	-	15	-	-	15
Replace screw parts kit	-	-	555	-	-	-	-	-	555	-	-	-	-	-	555
Replace motor bearings	-	-	333	-	-	333	-	-	333	-	-	333	-	-	333
Replace complete gas/end screw compressor	-	-	-	-	-	4,042	-	-	-	-	-	4,042	-	-	-
Maintenance costs	**2,004**	**2,128**	**5,036**	**2,004**	**2,128**	**8,398**	**2,004**	**4,132**	**3,032**	**2,004**	**4,632**	**6,394**	**4,132**	**2,004**	**3,032**
Yearly sorbent replacement costs	11,635	11,635	11,635	11,635	11,635	11,635	11,635z	11,635	11,635	11,635	11,635	11,635	11,635	11,635	11,635
Yearly electricity consumption compressor, blower, chillers	12,877	12,877	12,877	12,877	12,877	12,877	12,877	12,877	12,877	12,877	12,877	12,877	12,877	12,877	12,877
Total O&M costs	**26,516**	**26,639**	**29,547**	**26,516**	**26,639**	**32,910**	**26,516**	**28,643**	**27,543**	**26,516**	**29,143**	**30,906**	**28,643**	**26,516**	**27,543**

Finally, Figure 13 shows the disaggregated maintenance costs per kW, and Figure 14 shows the disaggregated total operation and maintenance costs per kW for the clean-up system.

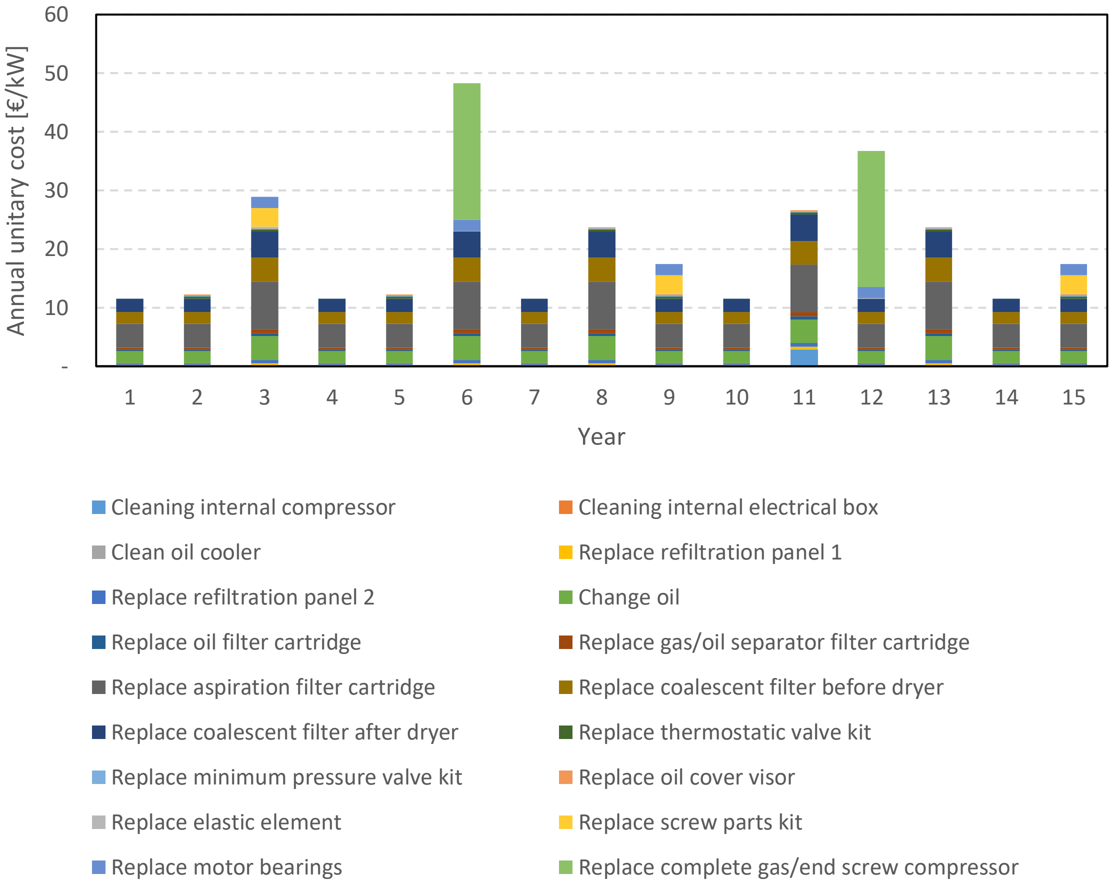

Figure 13: Clean-up system unitary maintenance costs

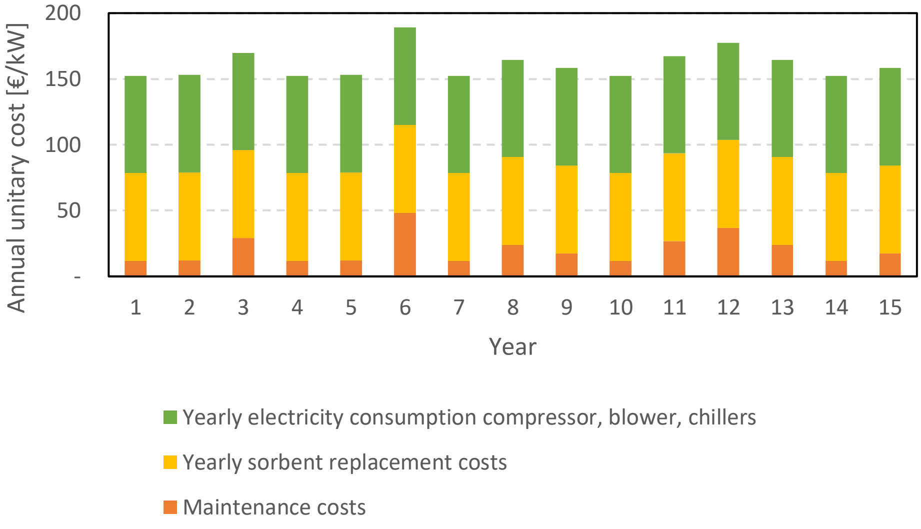

Figure 14: Clean-up system unitary operation and maintenance costs

Optimised scenario

The previous costs refer to the real DEMOSOFC pilot plant, which represent the costs of an oversized system. This section presents an estimation of a scaled-down generic system.

In the DEMOSOFC pilot plant, 1 blower and 2 chillers were necessary because the anaerobic digester was located far from the Biokomp unit. The optimised generic plant considers that only 1 chiller is necessary in a generic WWTP, thus 1 chiller and 1 blower are removed. It also considers that the plant could go from 6 to 3 siloxane and sulphur removal vessels, 2 vessels replaced yearly, one for sulphur and one for siloxanes removal.

Table 14 shows the parameters used to calculate yearly sorbent costs for the cleaning up plant, based on these new assumptions.

Table 14: Yearly sorbent replacement costs- optimised scenario

Number of vessels	3	
Number of vessels replaced per year	2	
Sorbents per vessel	250	kg
Total sorbent requirement	500	kg
Sorbent costs	5	€/kW
Labour	Assumed 10%	% of total cost
Cost for AC replacement	2,750	€
Sorbent disposal costs	8,885	
Total yearly cost	**11,635**	**€**

Table 15 shows the parameters used to calculate costs of the compressor's and chiller's electricity consumption.

Table 15: Compressor electricity costs

	Nominal power	
Compressor	4	kW
Chiller	2.5	kW
	Electricity consumption	
Capacity factor	0.957	
Yearly consumption	54492	kWh
Electricity cost	0.16 [9]	€/kWh
Yearly electricity cost	**8,719**	**€/y**

Table 16 shows the updated yearly total operation and maintenance costs for the cleaning-up system. As the optimised scenario includes only one chiller and no blower, summed O&M costs were reduced by 10% at the end, as it was unclear how to distinguish the O&M costs associated to this specific equipment.

Table 16: Yearly operation and maintenance cleaning-up optimised plant costs

Activity	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cleaning internal compressor	-	-	-	-	-	-	-	-	-	-	500	-	-	-	-
Cleaning internal electrical box	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Clean oil cooler	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Replace refiltration panel 1	41	41	82	41	41	82	41	82	41	41	82	41	82	41	41
Replace refiltration panel 2	52	52	103	52	52	103	52	103	52	52	103	52	103	52	52
Change oil	354	354	708	354	354	708	354	708	354	354	708	354	708	354	354
Replace oil filter cartridge	41	41	83	41	41	83	41	83	41	41	83	41	83	41	41
Replace gas/oil separator filter cartridge	63	63	126	63	63	126	63	126	63	63	126	63	126	63	63
Replace aspiration filter cartridge	706	706	1,411	706	706	1,411	706	1,411	706	706	1,411	706	1,411	706	706
Replace coalescent filter before dryer	353	353	706	353	353	706	353	706	353	353	706	353	706	353	353
Replace coalescent filter after dryer	394	394	789	394	394	789	394	789	394	394	789	394	789	394	394
Replace thermostatic valve kit	-	61	61	-	61	-	-	61	61	-	61	-	61	-	61
Replace minimum pressure valve kit	-	28	28	-	28	-	-	28	28	-	28	-	28	-	28
Replace oil cover visor	-	35	35	-	35	-	-	35	35	-	35	-	35	-	35
Replace elastic element	-	-	15	-	-	15	-	-	15	-	-	15	-	-	15
Replace screw parts kit	-	-	555	-	-	-	-	-	555	-	-	-	-	-	555
Replace motor bearings	-	-	333	-	-	333	-	-	333	-	-	333	-	-	333
Replace complete gas/end screw compressor	-	-	-	-	-	4,042	-	-	-	-	-	4,042	-	-	-
90% Maintenance costs	**1,803**	**1,915**	**4,532**	**1,803**	**1,915**	**7,558**	**1,803**	**3,718**	**2,728**	**1,803**	**4,168**	**5,755**	**3,718**	**1,803**	**2,728**
Yearly sorbent replacement costs	11,635	11,635	11,635	11,635	11,635	11,635	11,635	11,635	11,635	11,635	11,635	11,635	11,635	11,635	11,635
Compressor and chiller yearly electricity consumption	8,719	8,719	8,719	8,719	8,719	8,719	8,719	8,719	8,719	8,719	8,719	8,719	8,719	8,719	8,719
Total O&M costs	**22,157**	**22,269**	**24,886**	**22,157**	**22,269**	**27,912**	**22,157**	**24,072**	**23,082**	**22,157**	**24,522**	**26,108**	**24,072**	**22,157**	**23,082**

Finally, Figure 15 shows the total operation and maintenance costs per kW for a generic clean-up system.

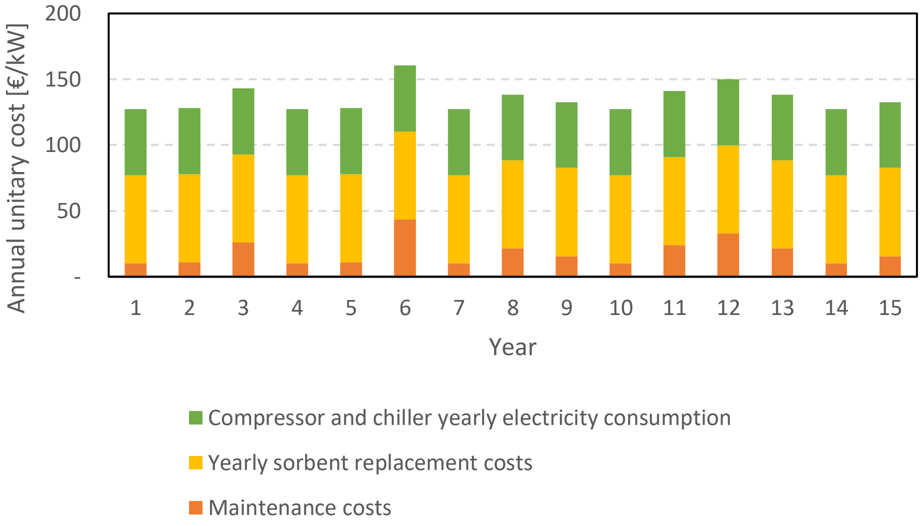

Figure 15: Clean-up system unitary operation and maintenance costs

3.3.2 SOFC system

Table 17 shows the operating and maintenance costs of the SOFC system, excluding stack replacement, together with the lifetime parameters, according to [10].

Table 17: SOFC system operation and maintenance costs, excluding stack replacement [10].

	100 kW units	**250 kW units**
Scheduled maintenance (yearly)	1720 €	2580 €
O&M	0.0258 €/kWh$_e$ (0.03 USD/kWh$_e$)	
Load factor	0.957	
Lifetime	15 years	

Table 18 shows scenarios for stack replacements, according to current costs and projections [11].

Table 18:Stack replacement cost scenarios [11]

Stack replacement scenarios	**Stack replacement frequency**	**Cost per replacement**
Optimal scenario: 8-years stack lifetime	1 replacement at year 8	24,000 € per 50 kWel unit
Intermediate scenario: 5-years stack lifetime	1 replacement at year 5, and 1 replacement at year 10	61,150 € per 50 kWel unit
Current scenario: 5-years stack lifetime	1 replacement at year 5, and 1 replacement at year 10	135,000 € per 50 kWel unit

4. DEMOSOFC life cycle costs

This section calculates the levelized cost of energy from a DEMOSOFC project, using the cost components and scenarios presented in the previous section. The calculations use the optimised costs for the capital and O&M site preparation and cleaning-up system costs, and the presents a range of results depending on the yearly production scenarios for the SOFC system costs. Table 19 shows the additional parameters used for the life cycle cost analysis.

Table 19: Life cycle cost parameters

Parameter	Value
DEMOSOFC lifetime	15 years [10]
Load factor	0.957 [10]
SOFC electrical efficiency	0.5 [3]
SOFC overall efficiency	0.85 [7]
Discount rate	12%

The levelized cost of energy is calculated as the net present value of the total system costs, including capex and opex, over the net present value of the total energy generated in the project's lifetime, as shown in Equation (1) as follows:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (1)$$

Where:

$LCOE$ is the levelized cost of energy

I_t is the investment cost in year t

$O\&M_t$ is the operation and maintenance costs in year t

E_t is the total energy production in year t

r is the discount rate

n is the lifetime of the project

The capital costs included are the total site preparation costs and the SOFC system capital costs. The operation costs included are the total O&M of the clean-up system, energy costs, the yearly O&M of the SOFC systems, and the stack replacements of the SOFC systems according to the scenarios mentioned in Table 18.

4.1 Scenario definition

The LCOE will be calculated for 100 kW and 250 kW units, for the following scenarios and their combinations:

1) Site preparation capital costs:

   a) Optimised scenario
   b) Current scenario
2) Annual SOFC production rates:
   a) 100
   b) 1000
   c) 10000
   d) 50000
3) Stack replacement scenarios (see Table 18)
   a) Optimal scenario
   b) Intermediate scenario
   c) Current scenario

4.2 LCOE results

Table 20 shows the annual costs for a DEMOSOFC project for these assumptions, in a per kW basis, for 100 kW and 250 kW units, for different production rate scenarios, and for the different stack replacement and site preparation capital cost scenarios.

Table 20: Life-cycle cost components (€/kW)

Unit size	**Annual production rate scenarios**	**Cost component (€/kW)**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 6**	**Year 7**	**Year 8**	**Year 9**	**Year 10**	**Year 11**	**Year 12**	**Year 13**	**Year 14**	**Year 15**
All	All	Clean-up system total O&M	127	128	143	127	128	160	127	138	133	127	141	150	138	127	133
All	All	Site preparation capital cost: Optimised scenario	2,531														
		Site preparation capital cost: Current scenario	6,024														
100 kW	All	SOFC system total O&M cost	233	233	233	233	233	233	233	233	233	233	233	233	233	233	233
250 kW			227	227	227	227	227	227	227	227	227	227	227	227	227	227	227
All	All	SOFC stack replacement: Optimal scenario								480							
		SOFC stack replacement: Intermediate scenario					1,223					1,223					
		SOFC stack replacement: Current scenario					2,700					2,700					
100 kW	100	SOFC system capital cost	2,494														
	1000		1,970														
	10000		1,733														
	50000		1,585														
250 kW	100	SOFC system capital cost	1,755														
	1000		1,427														
	10000		1,260														
	50000		1,153														

Using these costs and the assumptions in Table 19, the levelized cost of energy is calculated, considering total energy production for heat and electricity. The results are presented in Table 21.

Table 21: Levelized cost of energy for DEMOSOFC projects, different production rate scenarios.

Unit size	**Annual production rate scenarios**	**SOFC stack replacement scenarios**	**LCOE (€/kWh)**	
			Optimised site preparation costs scenario	**Current site preparation costs scenario**
100 kW	100	Optimal scenario	0.077	0.111
	1000		0.072	0.106
	10000		0.070	0.103
	50000		0.068	0.102
100 kW	100	Intermediate scenario	0.087	0.120
	1000		0.082	0.115
	10000		0.079	0.113
	50000		0.078	0.111
100 kW	100	Current scenario	0.101	0.134
	1000		0.096	0.129
	10000		0.094	0.127
	50000		0.092	0.126
250 kW	100	Optimal scenario	0.070	0.104
	1000		0.067	0.100
	10000		0.065	0.099
	50000		0.064	0.098
250 kW	100	Intermediate scenario	0.080	0.113
	1000		0.076	0.110
	10000		0.075	0.108
	50000		0.074	0.107
250 kW	100	Current scenario	0.094	0.127
	1000		0.091	0.124
	10000		0.089	0.122
	50000		0.088	0.121

The ranges of the levelized cost of energy for a DEMOSOFC project with a 100 kW or a 250 kW SOFC are compared with levelized energy costs of other technologies, as shown in Figure 16. The ranges for the DEMOSOFC costs correspond to the range of production rate scenarios.

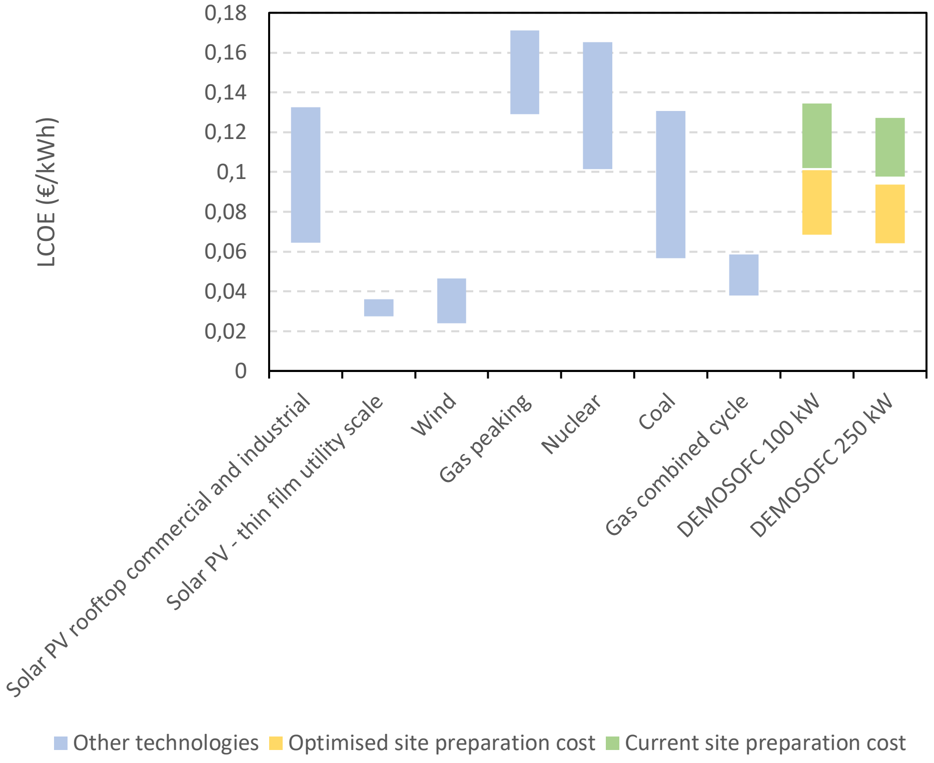

Figure 16: Based on [12] and own calculations.

As observed in the figure, DEMOSOFC projects are still in the high ends of levelized cost of energy ranges. Examining results shown in Table 21, it is observed that stack replacement scenarios are critical bottlenecks for technology cost-effectiveness. In higher production rate scenarios, which ensure capital cost decreases in the future, the scenarios for optimised site preparation costs are seen to be competitive with other energy provision technologies, such as solar PV, and coal power plants. When comparing DEMOSOFC with gas combined cycle levelized costs, it can be observed that the lower ends of DEMOSOFC projects, which correspond to optimal stack replacement scenarios, could be competitive. Also, DEMOSOFC levelized costs are in the same ranges or coal, nuclear, and gas peaking power stations. This means that in some cases it could be more convenient to install DEMOSOFC systems to cover energy needs in WWTPs. DEMOSOFC projects would also bring other benefits not costed here, such as carbon emissions reductions and energy security, when comparing to other gas technologies to provide energy needs to WWTPs.

5. Added value DEMOSOFC project

The DEMOSOFC project is not only a sum of its components. Value is added at each stage of the manufacturing process of its components and of its supply chain. This section aims to identify different elements of added value across its supply chain. Some of these elements are:

1) Labour
    a) Captured by local companies where the DEMOSOFC plant is located, by employing people to perform O&M activities of the DEMOSOFC and other units.
    b) Captured by local equipment suppliers and installers
    c) Captured by the fuel cell manufacturing company, where it is located
2) Margin
    a) Captured by local suppliers of equipment
    b) Captured by SOFC suppliers
3) Security of energy supply
    a) Captured by the WWTP, ensuring security of supply, energy self-sufficiency, and not being subject to varying fuel and electricity prices
4) Lower air pollution levels
    a) Captured by end-users and workers at the DEMOSOFC plant, who see a reduction in pollutant emissions

The following sections describe these different elements, and when possible, attempt to give a value for these. The values are giving in net present value per kWel (NPV), assuming a 12% discount rate and 15 years lifetime.

5.1 Labour

5.1.1 Captured by local companies where DEMOSOFC plant is located

The DEMOSOFC plant involves a series of O&M activities around the SOFC, but also around the cleaning-up and heat recovery systems. Local companies employ people to perform these activities. Cost of labour was assumed to be 10% of yearly O&M costs presented in Section 3.3.1, as no better estimate could be obtained. This element has a net present value of 63.6 €/kWel. This means that local companies would be earning 63.6 €/kWel in terms of labour incomes.

5.1.2 Captured by local equipment suppliers and installers

Local equipment suppliers and installers employ workers for the site preparation, heat recovery, and cleaning-up system installation. In Section 3.1, costs were disaggregated by different types of works, and further into components. From all the works described, only the Mechanical works had an explicit disaggregation of labour costs, corresponding to 23% of the total mechanical work capital costs. Therefore, this percentage was used as reference to calculate the total value added by labour for local equipment suppliers and installers, for the activities corresponding to site preparation capital costs. The value of labour is presented in Table 22.

Table 22: Value of labour for site preparation and installation activities

Actual scenario [€/kWel]	Optimised scenario [€/kWel]	% total
1,385	582	23%

5.1.3 Captured by fuel cell manufacturing company

This value corresponds to the value added by labour when manufacturing SOFC components, subsystems, and systems. According to a report by E4Tech [7], the value of labour corresponds to 54% of the total SOFC cost. Table 23 shows the values for the scenarios described in Section 3.2.

Table 23: Value of labour for SOFCs.

SOFC unit size	**100 kW**				**250 kW**			
Production rate scenarios (units/year)	100	1000	10000	50000	100	1000	10000	50000
Labour cost [€/kWel]	1,347	1,064	936	856	948	771	681	623

5.2 Margin

5.2.1 Captured by local suppliers of equipment

Local equipment suppliers and installers see a margin value in the costs for site preparation and equipment installation. It was not possible to disaggregate these costs from the total installation costs presented in Section 3.1, so two scenarios are presented in Table 24: one assuming 10% margin, and one assuming 25% margin.

Table 24: Margin value for local equipment suppliers/installers for 2 margin scenarios.

	Actual cost scenario [€/kW]	**Optimised scenario [€/kW]**
10% margin	602	253
25% margin	1,506	633

5.2.2 Captured by SOFC suppliers

This value corresponds to the margin value captured by SOFC manufacturers. According to E4Tech [7], the margin corresponds to 23% of the total SOFC cost [7]. Table 25 shows the values for the scenarios described in Section 3.2.

Table 25: Margin value for SOFC manufacturers.

SOFC unit size	**100 kW**				**250 kW**			
Production rate scenarios (units/year)	100	1000	10000	50000	100	1000	10000	50000
Margin value [€/kWel]	574	453	399	365	404	328	290	265

5.3 Security of energy supply

The DEMOSOFC plant (and others to potentially follow), create other values that are more subjective in terms of costs. Two of these elements are described here.

5.3.1 Captured by the WWTP, ensuring security of supply, energy self-sufficiency, and not being subject to varying fuel and electricity prices

The DEMOSOFC project generates biogas which is used to generate heat and electricity for the WWTP self-use. This means that the WWTP plant is nearly self-sufficient in terms of energy needs, as it can self-supply all of its heating needs and a big portion of its electricity needs. Thus, the plant has security of supply in the case that there is some major blackout in the electricity/gas utilities/distributors. Additionally, this means that the WWTP is not subject to electricity and gas price variations.

5.4 Lower air pollution levels

5.4.1 Captured by end-users and workers at the DEMOSOFC plant, who see a reduction in pollutant emissions

SOFC emit very low emissions at combustion. Compared to the original plant, where the heating needs were supplied by a gas boiler and all electricity was consumed from the grid, the DEMOSOFC creates a value to the local community through the decrease in emission levels. Table 26 summarises the measured emissions at the plant, and compares it with alternative technologies. This means that better air quality is achieved, with the subsequent benefits to health and climate.

Table 26: Summary of measured steady-state emissions from DEMOSOFC [13].

Species	Unit	Measured value	Typical emission limits of gas engines and turbines
H_2O	Vol-%	4.7	
CO_2	Vol-%	3.4	
CO	mg/m^3	<9	100
CH_4	mg/m^3	<2	
N_2O	mg/m^3	<8	
NO	mg/m^3	<20	
NO_x (as NO_2)	mg/m^3	<20	75-200
SO_2	mg/m^3	<8	15-60
C_2H_6	mg/m^3	<14	
HCHO	mg/m^3	<7	
HF	mg/m^3	<10	
HCl	mg/m^3	<10	
O_2	Vol-%	18.3	
Particulate	mg/m^3	0.01	Ambient air EU reference values 0.025 (PM2.5), 0.05 (PM10)

6. Final remarks

This report presents a bottom-up cost assessment of a DEMOSOFC system, composed by the WWTP site preparation and retrofitting, the installation of the cleaning system and SOFC system, and the operating and maintenance costs for a DEMOSOFC project. The total cost has been calculated in a kW basis, for a range of scenarios corresponding to different SOFC production rates.

The LCOE was calculated for these production rates and stack replacement scenarios. Results showed that 100 kW DEMOSOFC plants could obtain a LCOE ranging from 0.068-0.134 €/kWh, while 250 kW projects could obtain a LCOE between 0.064 and 0.127 €/kWh. While these are still in the high end of existing mature technologies, these LCOEs are comparable with high end LCOEs for gas combined cycles, and bring other benefits such as reduced emissions and WWTP energy self-sufficiency.

Finally, an assessment of the value added by a DEMOSOFC project at different stages of the manufacturing process of its components and of its supply chain is presented. Some of these added values were monetarised, while others were qualitatively characterised. Different activities that added/captured value from this project included labour from manufacturing companies and local companies performing O&M; the margin for manufacturers of the SOFC and other equipment; security of energy supply captured by the WWTP by enhancing energy self-sufficiency and stable energy costs; and lower air pollution levels captured by end-users and workers of the DEMOSOFC plant.

7. References

[1] Gandiglio M, Lanzini A, Santarelli M, Acri M, Hakala T, Rautanen M. Results from an industrial size biogas-fed SOFC plant (the DEMOSOFC project). International Journal of Hydrogen Energy. 2020;45(8):5449-64.

[2] Convion. Convion Fuel Cell Systems 2020 [Available from: http://convion.fi/products/.

[3] Langnickel H, Rautanen M, Gandiglio M, Santarelli M, Hakala T, Acri M, et al. Efficiency analysis of 50 kWe SOFC systems fueled with biogas from waste water. Journal of Power Sources Advances. 2020;2:100009.

[4] Madi H, Lanzini A, Diethelm S, Papurello D, Van herle J, Lualdi M, et al. Solid oxide fuel cell anode degradation by the effect of siloxanes. Journal of Power Sources. 2015;279:460-71.

[5] Gandiglio M, Lanzini A, Soto A, Leone P, Santarelli M. Enhancing the Energy Efficiency of Wastewater Treatment Plants through Co-digestion and Fuel Cell Systems. Frontiers in Environmental Science. 2017;5(70).

[6] D'Amico D. Optimization of the DEMOSOFC plant design to reduce plant costs and increase the market uptake of SOFC technologies: Politecnico di Torino; 2019.

[7] E4tech. Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies - Evidence Report. London, UK: E4tech; 2019 September 2019.

[8] Battelle Memorial Institute. Manufacturing Cost Analysis of 100 and 250 kW Fuel Cell Systems for Primary Power and Combined Heat and Power Applications. Columbus, OH, USA: Battelle Memorial Institute; 2016 January 2016.

[9] Mehr AS, Gandiglio M, MosayebNezhad M, Lanzini A, Mahmoudi SMS, Yari M, et al. Solar-assisted integrated biogas solid oxide fuel cell (SOFC) installation in wastewater treatment plant: Energy and economic analysis. Applied Energy. 2017;191:620-38.

[10] Scataglini R, Mayyas A, Wei M, Han Chan S, Lipman T, Gosselin D, et al. A Total Cost of Ownership Model for Solid Oxide Fuel Cells in Combined Heat and Power and PowerOnly Applications. Ernest Orlando Lawrence Berkeley National Laboratory; 2015 Devember 2015.

[11] Roland Berger Strategy Consultants. Advancing Europe's energy systems: Stationary fuel cells in distributed generation. Luxemburg: Publications Office of the European Union: FCH JU; 2015.

[12] Lazard. Levelized Cost of Energy and Levelized Cost of Storage 2019: Lazard; 2019 [Available from: https://www.lazard.com/perspective/lcoe2019.

[13] Rautanen M, Vesala H, Kajolinna T, Pellikka T. Analysis of the emissions from the DEMO - Deliverable number 4.3-a. VTT Technical Research Centre of Finland; 2018.

8. Acknowledgements

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

9. Appendix

POLITECNICO DI TORINO

Corso di Laurea Magistrale
in Ingegneria Energetica e Nucleare

Tesi di Laurea Magistrale

Optimization of the DEMOSOFC plant design to reduce plant costs and increase the market uptake of SOFC technologies

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Candidate
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A.A 2018/2019

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1. Abstract

Wastewater treatment is one of the most energy intensive public utilities. However, from this process, it is possible to produce biogas that is used, at the state of the art, as fuel for internal combustion engines (ICE). Nevertheless, the use of such technology has nowadays been brought into question because of its huge greenhouse gas emissions.

Wastewater treatment plants (WWTP) need a large amount of thermal energy to produce biogas in the digester that must be kept at around 40°C. Such temperature is an optimum for the bio-chemical reactions to take place and, consequently, for the generation of biogas. In this context, a CHP system would provide both thermal and electrical energy. If the former can be exploited in the digester, the latter can be used to feed the auxiliaries and reduce the purchase from the grid.

Moreover, from an economic point of view, the installation of a CHP system is expensive though they are partially financed by some of the countries of the European Union (EU) through incentives. This scenario has, therefore, led to an increasing interest towards a new technology which needs to be further analysed: the use of stacks of Solid Oxide Fuel Cell (SOFC) in WWTP. DEMOSOFC project has been thought from this point of view.

This new work has needed a huge design effort corresponding to a huge amount of cost of investment. For this reason, the main goal of this thesis is the re-engineering of these plant in order to have an important reduction of the realization cost. To achieve this purpose an accurate analysis on the realized works and on their cost has been performed. In this analysis each works has been evaluated and, in the final proposed re-engineering project, only the actually necessary works are kept, in order to have minimum realization cost of the plant.

Finally, a reduction of 56% concerning the site preparation cost is estimated. However, the total plant cost reduction that is evaluated is between 60% and 77%. In this way it is possible evaluate a comparison with the standard technology, then a penetration on the market of this technology is reasonable.

2. The DEMOSOFC project

The European Union (EU) has been showing an increasing interest towards environmentally friendly policies. In this view, in the 2014, the EU financed Horizon 2020 research and innovation programme. It is the biggest EU research programme in which €80 billion of funding are available over 7 years (2014 to 2020). Due to this programme, a large quantity of projects is being developing. Among these, there are some projects about the reduction of operational cost of WWTP. In fact, this kind of plant requires a huge quantity of energy. In example Castiglione WWTP (Turin, IT) is serving 2.7 million equivalent persons (EP) and it show an energy request of 66.78 GWh/y of electricity and 49.15 GWhth/y of thermal energy [1].

To achieve this purpose, it is necessary a retrofitting of the existing WWTPs. To do this, two new pathways can be analysed:

- Upgrade of biogas into biomethane;
- Use of biogas as fuel for SOFC;

Both are novelties in a market that is, nowadays, strictly linked to the use of ICEs. Then both the two alternatives, in particular way the second one, need a deeper analysis especially for what the economic feasibility is concerned.

This goal led to the funding, in 2015, of the European project named “DEMOSOFC” in the context of Hydrogen Europe and Hydrogen Europe research. DEMOSOFC is the abbreviation of “DEMOnstration of large SOFC system fed with biogas from WWTP”. It is a demonstration plant, because DEMOSOFC is the first biogas fed industrial size SOFC installation in Europe.

This project is based on the retrofitting of the already existing WWTP located in Collegno (Turin, IT). It is meant to be carried out through the installation of three SOFCs (58 kW each). In this way, they are able to guarantee the supply of around 30% of the site electrical consumption, and almost 100% of the thermal requirement [2]. In the current scenario, just two of them is actually working. Anyway, DEMOSOFC project have also another aim, which is that of analyse the market penetration of a new and eco-friendly technology, the SOFC one.

In conclusion, DEMOSOFC project on one hand aims to solve WWTP operating cost and on the other hand it aims at evaluating market penetration of SOFC in order to understand, weather EU will make some incentive available, if this technology will be competitive on the market.

2.1 Wastewater Treatment Plant

Wastewater treatment is a process that can remove, or break down, water pollutants. In other words, this process is able to convert wastewater into an effluent which can be returned to the water cycle or directly reused. In this last case, treated water can be used for lands irrigations. Anyway, its excessive use is discouraged because it can still contain high relative concentration of biosolids. They are the solid residues of wastewater treatment and, although they have good fertilizing properties, they usually contain higher concentrations of heavy metals [3]. Then, another option is utilizing biosolids in gasifier to obtain biogas.

This process takes place in a specific plant, called wastewater treatment plants. They can be distinguished by the type of wastewater to be treated, for example exist municipal sewage treatment plants, industrial wastewater ones, agricultural wastewater ones and leachate ones. Among these WWTP types, municipal sewage treatment plant is the most import type because it is the most used. In fact, when we talk about WWTP generally we refer to this specific type. Moreover, Collegno WWTP is exactly of this type.

2.1.1 Wastewater treatment process

In a WWTP, wastewater treatment process is subdivided in more than one process. In fact, it can be subdivided in:

- Separation Phase:

  In this phase there is the separation of the water from impurity into a non-aqueous phase. We can have the separation of grease and oil (that is recovered for fuel or saponification) and the first phase of separation of biosolid, that requires dewatering of sludge.

  Generally, this process is made in a pool called clarifier.

- Sedimentation:

  It is controlled by turbulence and gravity phenomena: the water that must be treated is mixed and in this way solids (like stone) are separated due to density differences. In conclusion, solids that are heavier then water will accumulate at the bottom.

  Generally, this process is made in a tank called primary sedimentation circular pond.

- Filtration:
  Suspensions of fine solids can form coagulations that must be removed by filtration through fine physical barrier.

- Oxidation:
  It is necessary because reduces the biochemical oxygen demand and it is used to convert organic compounds into carbon dioxide, water and biosolids. Another important effect of this treatment is the possibility of toxicity reduction of some impurities.

- Biochemical oxidation:
  This process is preferentially used to remove organic compounds from water. It is controlled by micro-organism that eat these compounds, then this process is named co-metabolism. Anyway, removal efficiency is limited by the digesting capability of micro-organism, as each biochemical process.

- Chemical oxidation:
  Chemical oxidation is performed after biochemical one and it used to remove the remaining organic compounds. Furthermore, this process is able to kill bacteria and microbial pathogens by adding ozone, chlorine or hypochlorite to wastewater.

- Polishing:
  After chemical oxidation, water needs a treatment to adjust pH to correct value. This treatment can solve this problem as well as the removal of last contaminants by activated carbon.

2.1.2 Collegno WWTP description

The WWTP of Collgno is a municipal sewage treatment plant. It is the second for dimension of the Metropolitan city of Turin and it is property of S.M.A.T. (Società Metropolitana Acque Torino). It has a mean capacity of depuration of 185000 EP, then a mean flowrate of 38400 cubic meters of sludge treated per day. Following figure shows Collegno WWTP.

Figure 1-Collegno WWTP aerial view

Then this plant has two main lines: one to wastewater treatment and the other is to sludge treatment. The second one start from the first and its aims is the biogas production.

Figure 2 shows the general layout of the plant with the required indication. The entering wastewater flowrate is split and it is sent to two treatment compartments called first and second module. Each module is composed by two primary sedimentation circular ponds (5) and four lines of pools for biological treatment (7-6) [4].

The biological treatment is based on a suspended biomass technology (active sludge) with pools divided in anoxic (denitrification (6)) and aerobic (nitrification (7)) environment. Once the biological treatment is concluded, the heaviest part is sent to some secondary sedimentation circular ponds that are used to increase the solid percentage (8); the part with a lower content of solid is sent to the disinfection treatment by chlorination (10) and in the filtration one (41), here the 20% is ultra-filtrated for internal use and to be sent to the aqueduct while the remaining part is flowed into the river. A gravitational pre-thickening treatment (11) is needed to increase the dry content before entering the mesophilic digesters (anaerobic digestion 12a-12b) that operates at a temperature of approximately 40 °C. The outlet flow from the digester receives a treatment of post-thickening (14) and of mechanical dehydration (15), the concentrated sludge is disposed by a company that reuse them in agriculture as fertilizers. Due to hourly and seasonal production variation, the produced biogas is stored in the gasometer (also called gas holder) that has a capacity of 1.470 m^3 (17). The maximum available storing capacity is1440 m^3. It is controlled by 4 level sensors: very low, low, high, very high. Then, biogas is fed to a boiler in order to cover the digester heat demand. In case an excess of biogas production is detected (rare cases), that is when sensor of ‘very high’ level is on, it is sent to the flare. In case heat production is not enough to heat up the sludge entering the digester (heat exchanger placed in (30)), natural gas is burned in a second boiler to provide auxiliary heat [4].

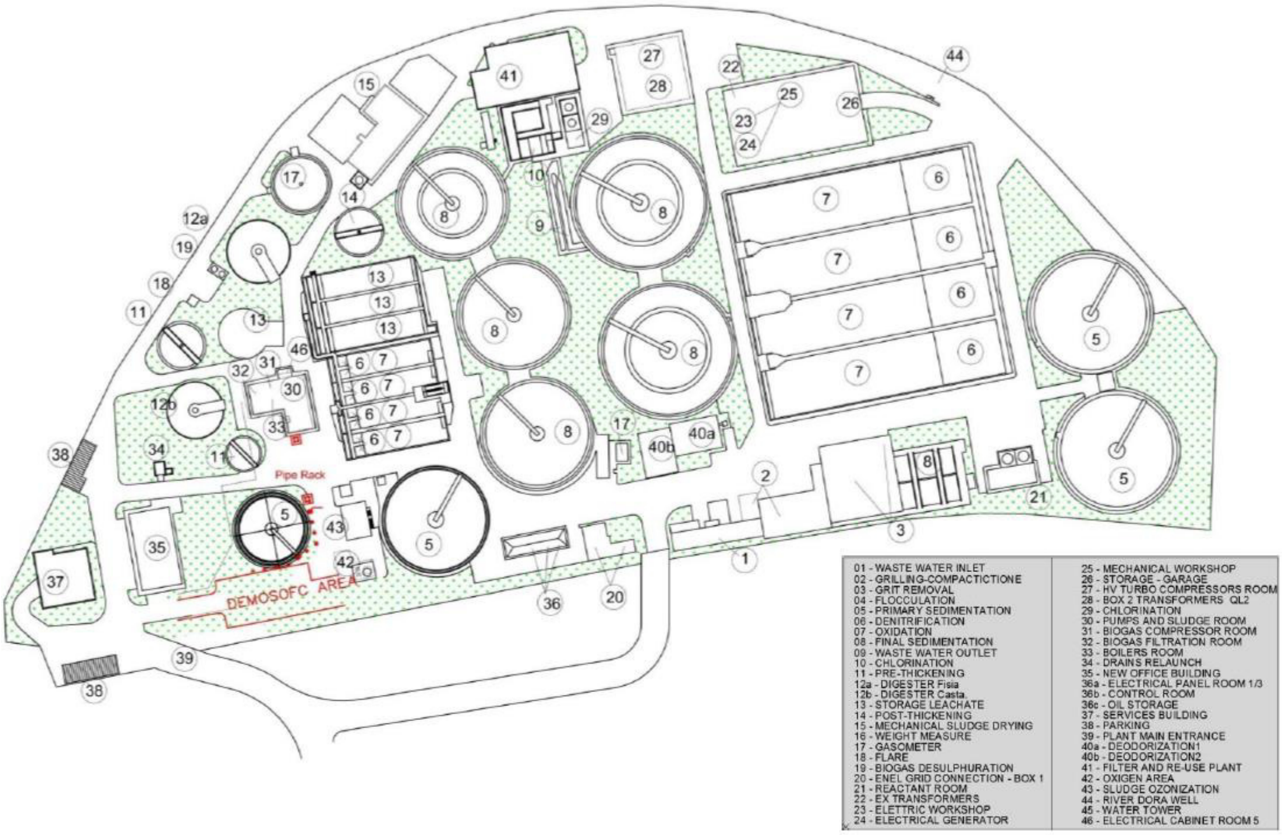


Figure 2-Collegno WWTP layout

The biogas production is characterised by big fluctuations during the year and during the day, as is shown in figure 3. Based on this trend, the nominal biogas flow rate to the modules was designed in order to maximize the biogas consumption in the modules and to maximize the nominal working time. Then, the nominal consumption of the fuel cells equal to 60 Nm^3/h was chosen. However, in some periods of the year could be necessary to decrease the electrical power of the SOFC modules [4].

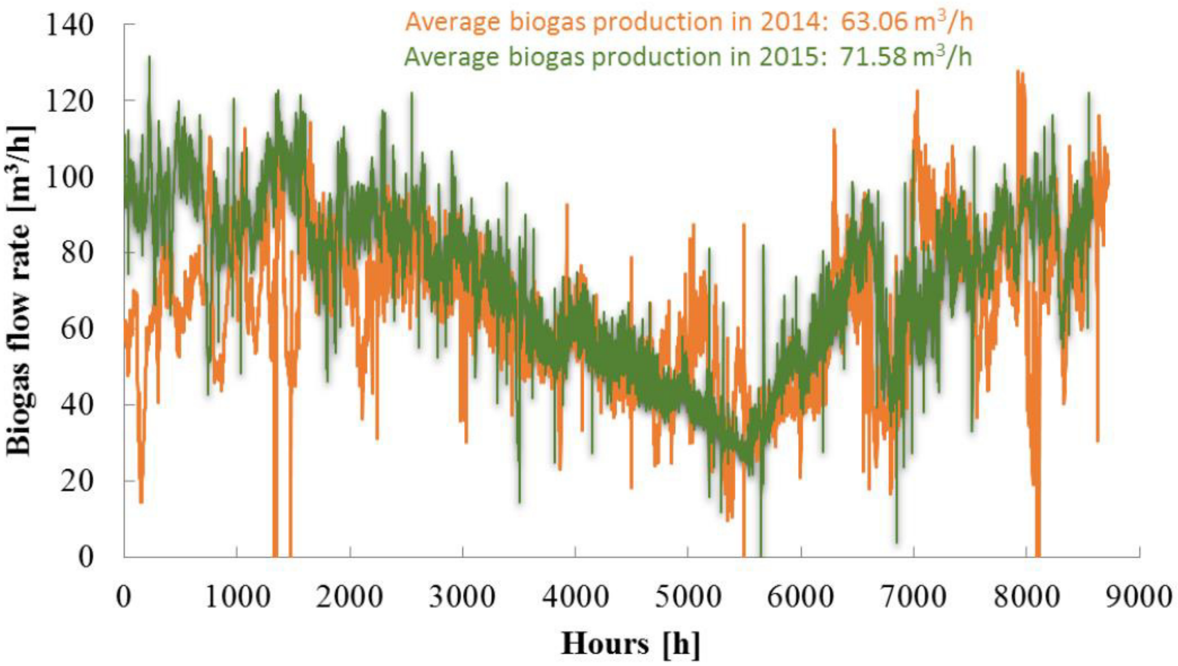


Figure 3-Annual fluctuation of the biogas production

2.2 DEMOSOFC retrofitting

As described above, Collegno WWTP produces biogas by the anaerobic digestion of the sludge and it is burned in a boiler in order to produce thermal energy able to heat digester.

Now, with DEMOSOFC retrofitting, the boiler is replaced by 3 SOFC modules in order to have a better biogas use and lower greenhouse gas emission. Another important aspect is the cogeneration, because the SOFC modules are able to produce both thermal energy and electric one. In this way, Collegno WWTP is eco-friendlier and its energy demand is decreased.

Anyway, to avoid fast degradation of fuel cells, produced biogas has to be strongly purified because it is rich of contaminants. Then, the new retrofitting consists 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 (actually only two of them are in operation)

- New 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.

To realize this retrofitting, various works were made. It was necessary built new pipelines, as well gas supply one and heat recovery one, in order to link pre-existing area to the new DEMOSOFC ONE. It is composed by the three SOFC modules, the clean-up container, auxiliary gas building and a technical building, where electrical cabinets and control room has been located. All these components are placed on a reinforce concrete basement. It is shown in the following figures. In the figure 4 it is possible to see a 3D sketch of new DEMOSOFC area. While in figure 5 it is shown the new pipelines, that are identified by yellow and blue continuous lines. Finally, figure 6 shows a simplified operating scheme of new area [5].

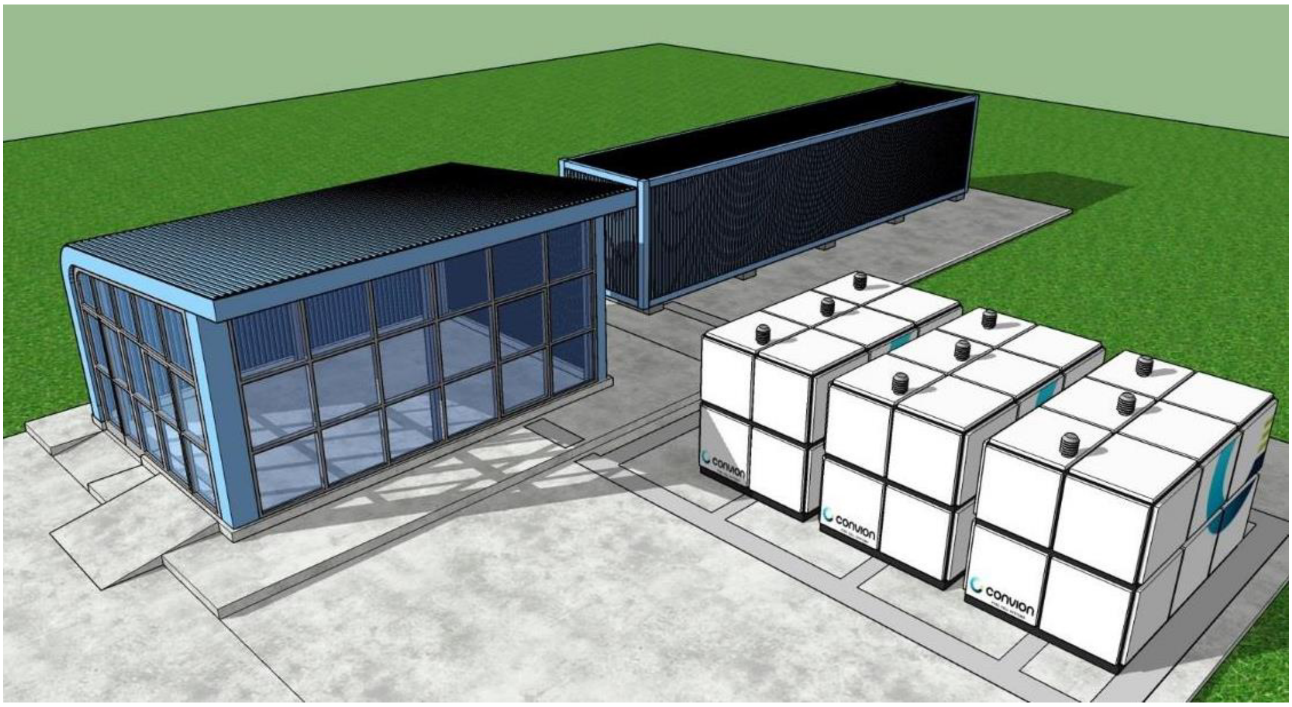


Figure 4-DEMOSOFC 3D sketch. Technical building at left; clean-up system at right; three SOFC modules

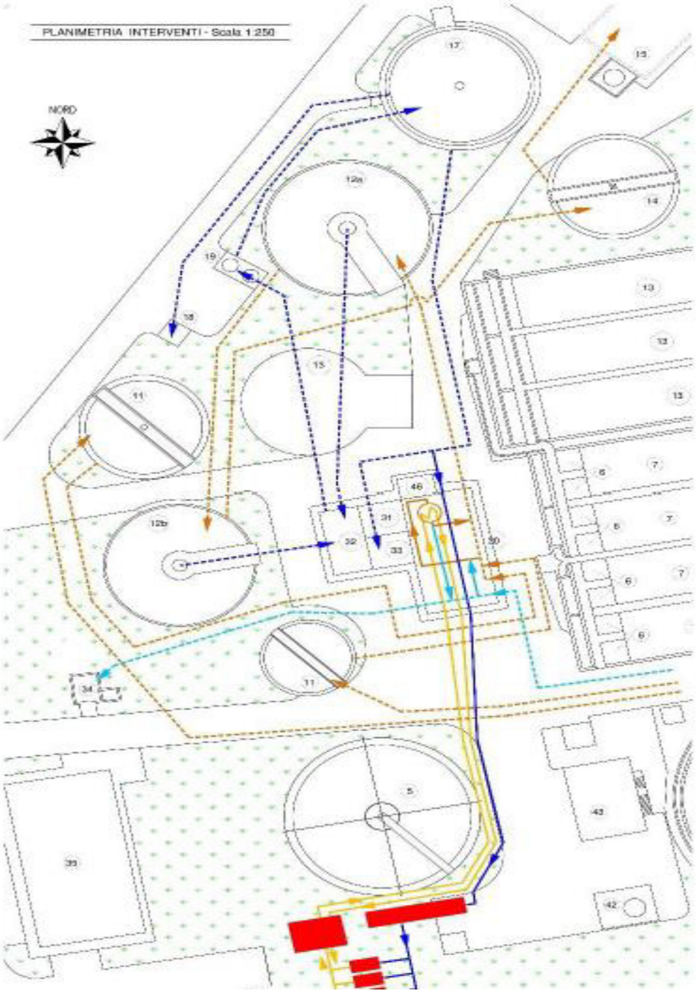


Figure 5-Process flow connection. The new pipeline are the continuous lines

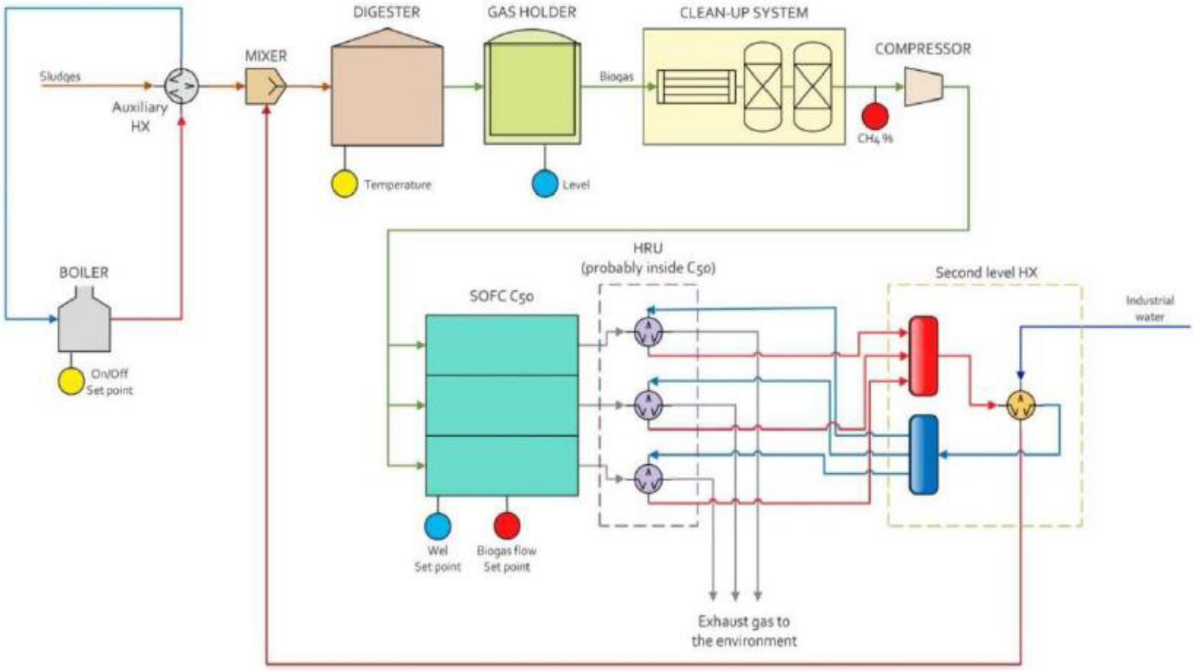


Figure 6-DEMOSOFC simplified operating scheme

2.2.1 Description of each unit

In this section a short description of each unit is reported.

2.2.1.1 SOFC unit

The three SOFCs modules has been provided by the Finnish company and partner of DEMOSOFC, Convion. The Convion C50 model was chosen. At this moment, only two of them are already working.

Figure 7-Convion C50 SOFC module

Convion C50 is a modular SOFC power generator and, at state of the art, it can produce 58 kWe. 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. In fact, at the beginning, there was only one module working. As mentioned before, now there are two modules working, but by project there will be three parallel modules working. In this view, the electrical power production of the whole system will be 174 kWe [5].

The whole system will be fed by 57.9 m^3/h of biogas for the three modules, with an average methane content of 63%. In order to work, each module needs also pre-cleaned and non-condensing pressurized air and process air, can be taken at ambient pressure [5].

All inputs and outputs of C50 SOFC module are summarized in the following figure in a schematic view:

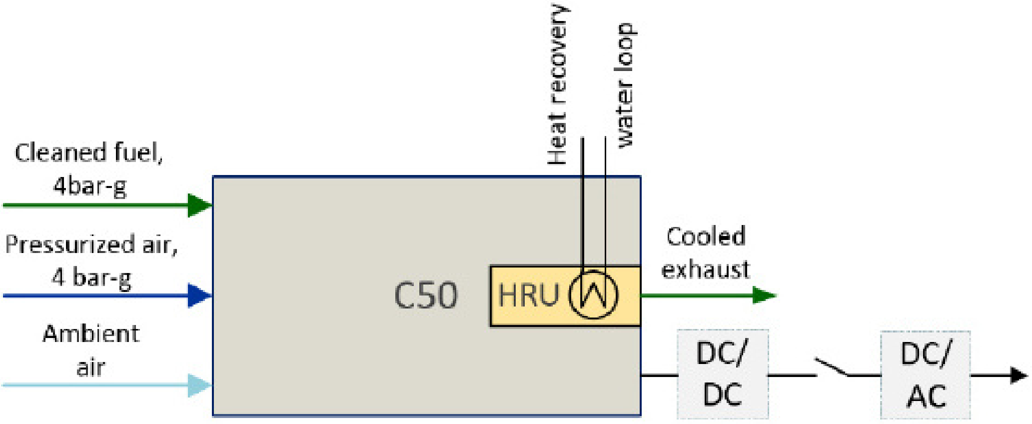
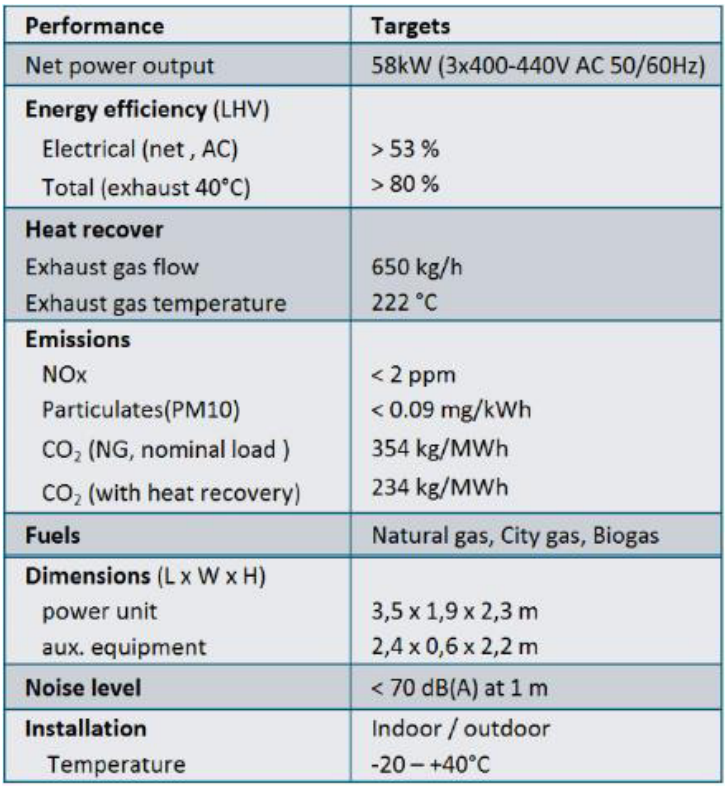


Figure 8-Inputs and outputs of C50 module

While in next figure is shown its datasheet:



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 9-C50 module datasheet

It is possible to note that, in addition to its high efficiency, this C50 module, as well as SOFC module in general, present very low values of pollution both towards noise pollution and regarding the emissions. It has a simple explanation: about the first it has not got rotating parts, while for the second one it is necessary to utilize a very clean fuel to prevent damage. In fact, input fuel must have the following characteristics:

- Max sulphur content: <30 ppb
- Siloxanes: < 10 ppb
- Halogen compounds: <1 ppm
- Allowed level of humidity: Non-condensing

To reach this strict characteristic, biogas must be treated in the clean-up system, that is described in the next section.

What has been described so far, is a normal operation, but also exists another input gas which is used either in emergency shut down operation or in hot stan-by, that is NH-mix (95% N_2, 5% H_2). This gas is also located on the concrete basement and it is strictly necessary in above mentioned situations in order to avoid damage or avoid cooling down of SOFC module [5].

2.2.1.2 Clean-up system

The clean-up system is used to clean, to compress and to dehumidify biogas feeding SOFC modules.

In order to choose the best clean-up configuration, a preliminary study on raw biogas contaminants concentration was performed. It was made from July 2015 to February 2016 [5]. Its trend is reported in the following figure:

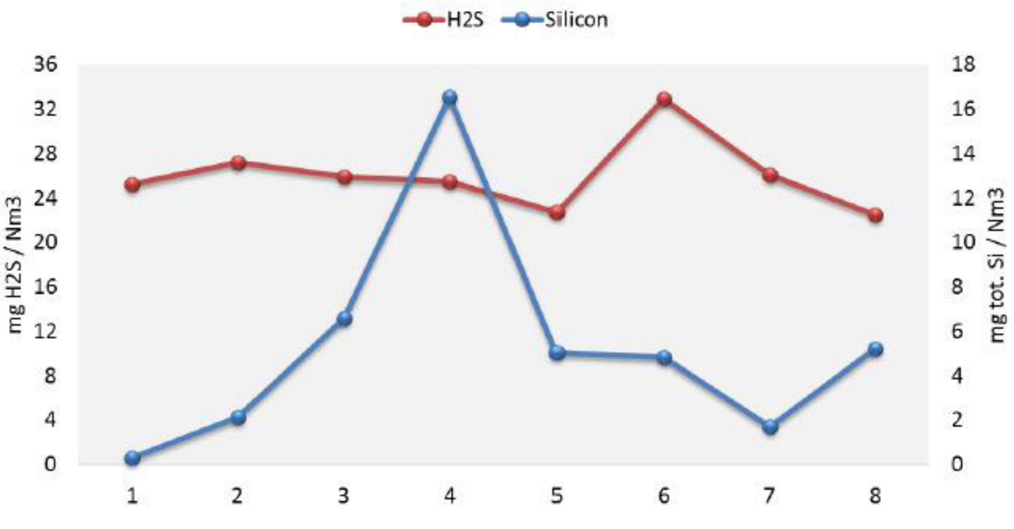


Figure 10-H2S and silicon trend during test operation

As it can be seen, these concentrations are very far from C50 request. Then, a very good lead and lag series reactors configuration was chosen. This unit was commissioned to Bio-komp S.r.l. . Furthermore, it has been requested in a container solution in order to have a conditioned area for biogas processing and due to safety reason, because in this way the supplier had to certify the clean-up section as a unique product.

In order to perform its aim, the clean-up system is composed of many components, later described. When raw biogas enters in this unit it goes through a gravel filter to cut the starting compounds concentration. Then, there is a blower to overcome the load losses and biogas comes to the clean-up core, the lead and lag configuration. It is a series of chemical reactors, where activated carbon catalysts are adopted to remove compounds down to SOFC requirements. This configuration is composed in a complicated reactors and valves configuration, and it can be subdivided in two equal columns. Each column is composed by two series connected reactors, one is utilized to remove mainly sulphur compounds and the other to remove mainly siloxanes compounds. Anyway, this configuration is able to keep into the loop raw gas until the analyser detects correct value of compounds. Moreover, this configuration can work continuously because when 'lead' column is saturated and then it needs change its carbon activated catalyst, 'lag' became a new 'lead' and the clean-up system can continue to work. The gas analyser utilized is made by Qualvista. It was chosen due to its high rate of accuracy about compounds measurement. Moreover, it can monitor CH4 and CO2 percentage and can show online, in real-time, each measurement.

After cleaning, biogas must be compressed to reach 4 barg required by SOFC modules. It is made through a compressor based on a single rotary group in single-stage oil-injected screw. Then, there are two dehumidification system composed by two chillers, where R410A refrigerant is used. Finally, there is a multiple filtration system, able to remove oil traces caused by compressor [5].

The whole clean-up system layout is summarized in the following figure:

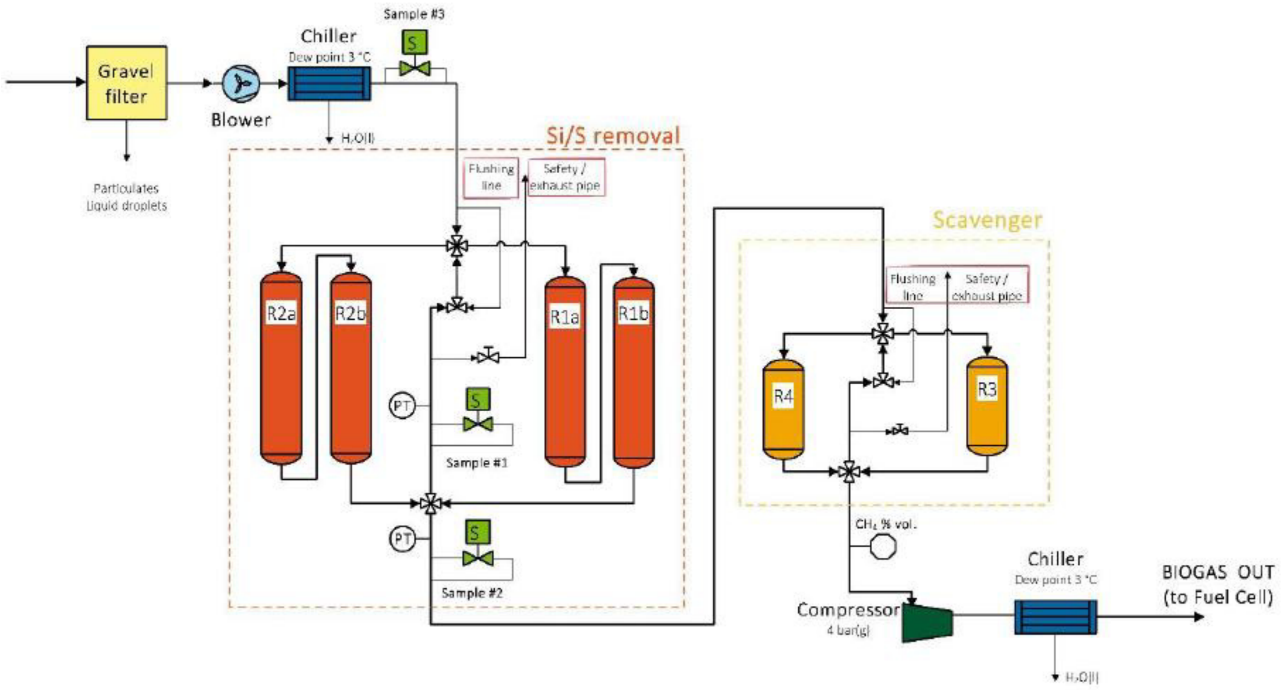


Figure 11-Clean-up system layout

2.2.1.3 Thermal recovery system from SOFC section

In this new configuration, the main thermal recovery system is composed by the gas-liquid heat exchanger (HE) located inside each the SOFC module: heat released for the hot exhaust gas is transferred to a water+glycol loop. Since there are three SOFC module, it means there are three gas-liquid HEs too. These three lines are connected together and sent to the second liquid-liquid HE, that is fed, on the other side, by the incoming sludges to the digester. In order to guarantee a continuous operation of this system, all the pumps in the water+glycol loop are doubled and they are installed in a parallel configuration. Instead, on the other side, the liquid-liquid HE is also fed by industrial water line, because, in case sludges are not available, heat removal is always guaranteed [5].

In case of either SOFC modules shut-down or no biogas available, the already existing boiler fed by natural gas is used. Then, in this way, it is possible to utilize the existing configuration as an integration of the new one and improve the availability of the plant.

The thermal recovery layout is summarized in a schematic view in the next figure. Moreover, nominal design temperatures are shown too.

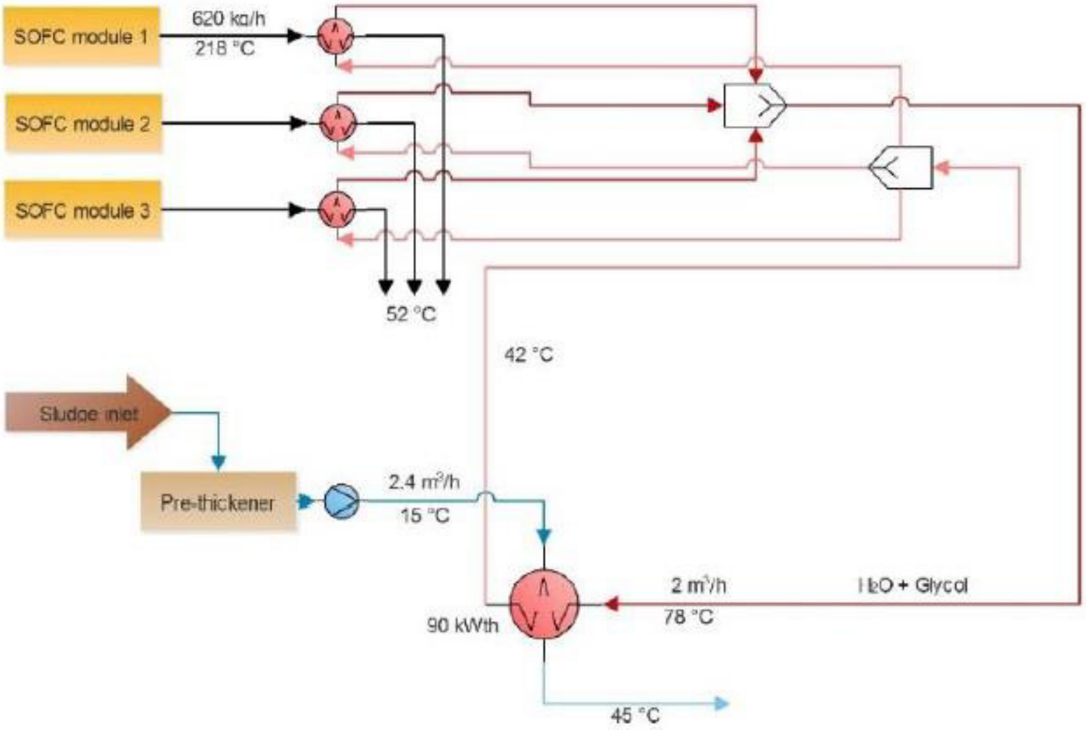


Figure 12-Thermal recovery layout with design temperatures

3. DEMOSOFC plant cost analysis

In this section, an analysis on the realized works and on their costs will be performed. First of all, short description of works is made and then an appraisal of the economic aspects related to this project will be shown in order to detect the bottlenecks of its realization. It will be done through a comparison between the cost estimation in the design phase performed by SMAT and the actual costs incurred during the construction phase. Although just two of the three SOFCs were installed, not big variation in the final actual cost of the plant will be expected. Therefore, the following results can be considered a good picture of the overall expenditure this installation would require.

For convenience, both the description and the analysis of cost, of the realized works are subdivided in five macrozones: Civil works, Mechanical works, Electrical Works, clean-up system and auxiliary works.

3.1 Description of realized works

Following there is a short description of each kind of work and then a more accurate description was performed.

- Civil Works:
  It includes realization of concrete basement, cable ducts to pipeline, pipe rack, realization of technical building, installation of SOFC modules and clean-up container and all the necessary works to security needed in building sites.
- Mechanical Works:
  It includes all the necessary to realize the pipelines of gas, technical gas, the compressed air and heat recovery unit line.
- Electrical Works:
  It includes the remaking of the medium voltage electrical cabinet, the realization of a panel dedicated to manage the loads of the DEMOSOFC area and all the necessary to realize electrical pipeline.
- Clean-up system:
  It includes only the production cost, because all works are performed by bio-komp.

- Auxiliary works:
  In this large category technical gas, gas analyser, connection to the grid works and unloading and positioning cost are included.

3.1.1 Civil works

These works are performed by Icef Sviluppi Immobiliari S.R.L.

3.1.1.1 Basement concreate realization

Due to the performed risk analysis, it was necessary to separate pipelines in order to avoid possible explosive atmosphere in the recirculation pumps. Then two cable duct lines have been built, one to compressed air and gases and the other to heat recovery, as figure 13 shows. Furthermore, they are built under the platform. In fact, the first step of the works was the excavation that was made down to a depth of about 80 cm. At this depth, besides cable ducts, a first plate of regulation is casted with a subfloor function. It is made in lean concrete with a thickness of 20 cm. Over this stratum, formwork and the armours are put in order to build the platform in reinforced concrete with a thickness of 60 cm. Finally, the completed platform is connected to the existing road by tarring in order to ensure accessibility [4].

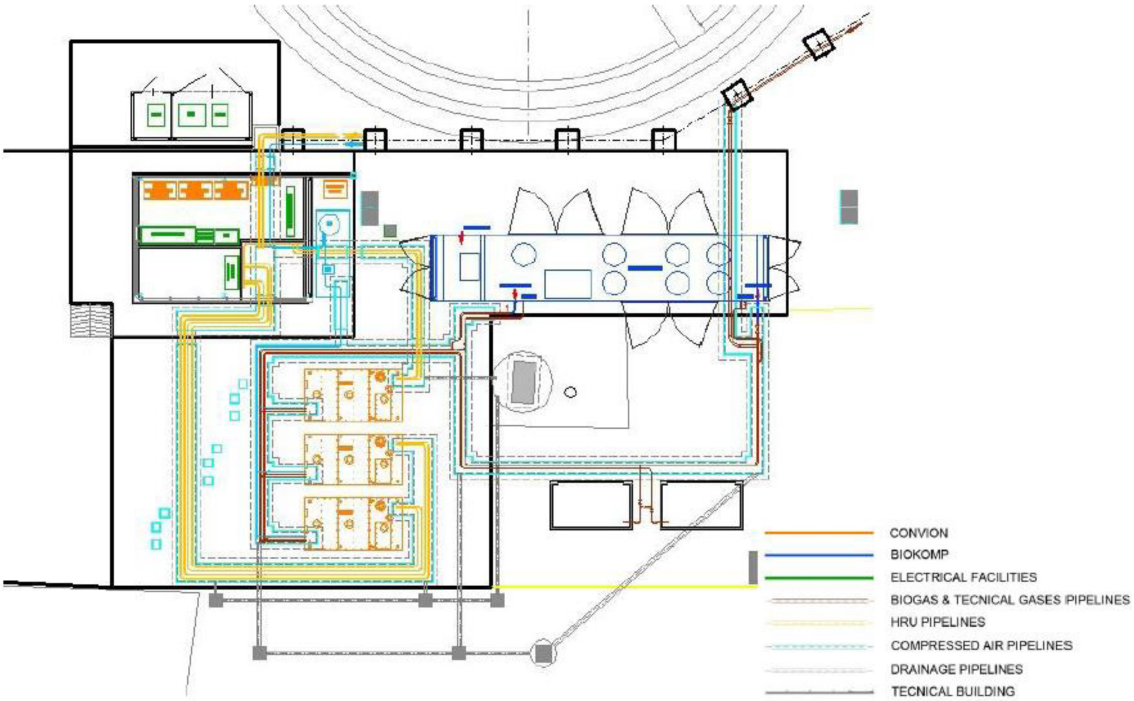


Figure 13- Pipelines layout

3.1.1.2 Pipe rack

Gas holder, where biogas is stored, is located far from the new DEMOSOFC area. Then, to fed biogas to the SOFC module, a pipeline is needed. To avoid excavation of a large area and to have pipes easily maintained, it is installed on racks. The racks consist of a lightweight steel structure composed by a reinforced concrete foundation plinth; they are made by a steel profiles in a double T-shaped suitably dimensioned and by a top shelf in steel section welded to the structure with appropriate reinforcement tools. Moreover, this rack had to pass above a road, then a trellis bridge was needed.

To realize this pipe racks, first of all, the plinths were realized, then excavation, formworks and armors were made. Then, steel armors assembling, both of trellis bridge and of pillars, was performed [4].

In next figure, on overview of this works is shown.

Figure 14-Pipe rack

3.1.1.3 Technical building

The technical building is composed by a unique structure subdivided in three different room one is used as control room and to host PLC monitors, another room is used to host the static converters and transformer and main electrical cabinet and switch, third room is used for primary HRU pumps.

The supporting structure is in steel, instead the coverage is made in insulated sheet steel. Two side of the boiling are realised in aluminium and glass profiles in order to give an aesthetic valence to the building.

Then, another building was needed to hold UPS and batteries. It is a closed environment because it must be conditioned since UPS generating heat, but batteries should work at a stable temperature of 20°C.

To build technical building, first the bearing structure was assembled, the insulated sheet steel and the internal division and glass were installed [4].

Figure 15-Technical building

3.1.2 Mechanical works

These works are performed by Coop. Viridia S.C.

In this section are reported all the works made to install each pipeline. Then, pipes, valves, measurement tools, chillers and blowers have been laid to biogas and technical gases pipelines. To heat recovery pipelines, besides the installation of pipes, valves, measurement tools, it was also needed the installation of pumps and the secondary tube in tube heat exchanger (liquid-liquid), instead the primary one is placed inside each SOFC modules. Finally, regarding air compress pipeline, it was needed to install pipes, filters, a storage tank and a chiller. Furthermore, in this section action cam installation works are included [4].

3.1.3 Electrical works

These works are performed by Baratella F.lli Srl.

In this kind of works it is considered the realization of grounded duct, installation of electric cables in duct, electric connections required by SOFC modules and clean-up system and the installation of all electrical connection required by DEMOSOFC. Moreover, the installation of electrical cabinet was performed. Finally, also if it is not strictly related to DEMOSOFC area, MV cabinet is changed and it is included in these works.

To realize grounded duct, excavation and casting were performed. When duct has been realized, electric cables are installed in order to connect DEMOSOFC area with the electrical cabinet located in technical building. Here have been also installed a switch cabinet, the CONVION interface cabinet, Programmable Logic Control (PLC) and a transformer. Instead, Uninterruptible Power Supply (UPS) was placed in another prefab box near the technical building [4]. A short description of each unit follows.

Switch cabinet must allow to connect or disconnect the different lines in a manual or automatic way. Here, the required tools to measure currents and power are installed.

In the electrical cabinet are placed PLC cabinet, supervision and measurement tools and the control system of each unit.

Convion interface cabinet includes control system of SOFC modules and the inverters to convert the electricity produced by each module.

Furthermore, also emergency button installation and the change of the monodirectional counter with a bidirectional one are included in this kind of works. This last operation was necessary due to the electric power production of SOFC modules and it has been performed by the network operator (ENEL) according to the current standard for user/producer customer [4].

3.2 Plant cost analysis

In this paragraph the plant cost analysis is described. It is performed in some steps. Initially, as before, the works are subdivided into macro areas. Then an analysis on each kind of works has been made based on the estimation of realization cost in the design phase. Subsequently, the same analysis is performed but now it is based on real (or actual) realization cost. Later, a study based on cost variation between estimated cost and real one has been performed. Finally, it was possible evaluate total DEMOSOFC cost and then the prize related installed kilowatt has been calculated.

Some documents, called '*Computo metrico estimativo*' (CME) [6][7] [8][9], are used to establish the estimated cost of realization in the design phase. They are realized before starting the works. These documents represent an accurate study on the work that will be realized, where quantity and prize of each component are reported. In this way it was possible to establish the total cost estimation. Based on these documents, each society has to propose a discount rate to apply at their cost estimation in order to win the tender procedure to realize these works.

On the other hand, the analysis that is performed on real cost and it has been made using documents called '*Stato di avanzamento lavori*' (SAL) [10][11] [12][13]. They are accurate documents that show the quantity and prize of the actually bought components and the cost of works realized until a specific time. Based on this document and on the discount rate established before, the real cost of each works is determined. Anyway, discount rate cannot be applied to all kind of works, as well safety cost.

The cost variation is performed analysing the same kind of work and it is evaluated as follows:

$$Cost\ variation\ (\%) = \frac{Actual\ cost - Expected\ cost}{Expected\ cost} * 100$$

The cost of main works, with the related variation, is summarized in the table below:

	Estimated Cost [€]	**Actual Cost [€]**	**Cost Variation**	**Security cost [€]**
Mechanical Works	186.439	174.562	-6,37%	5.255
Electrical Works	125.754	173.913	38,30%	6.113
Civil Works	128.701	191.920	49,12%	5.687

Clean-up system	215.965	221.087	2,37%	6.500
Auxiliary works	83.258	91.677	10,11%	0
TOTAL	740.116	853.159	15,27%	23.555

Table 1-Comparison between estimated and real cost of the main works

It is also shown in the figures below:

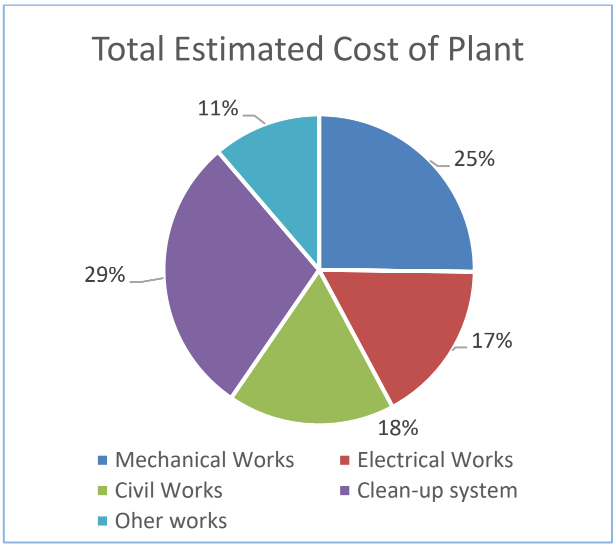


Figure 16- Division of the estimated cost

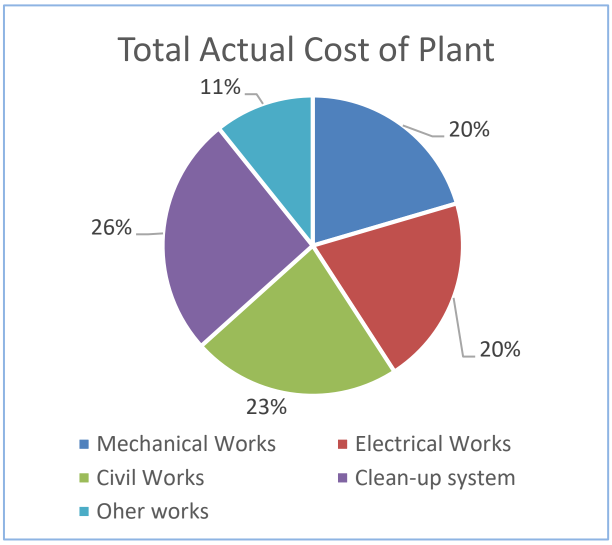


Figure 17-Division of the actual cost

The main result that shows these data is the huge cost of the site preparation plant. In fact, the ratio between this cost and the plant size is:

$$\frac{Site\ prepation\ cost}{Plant\ size} = \frac{853.159€}{174\ kWe} = 4.900\ \frac{€}{kWe}$$

Then, this ratio express, in an explicit way, its huge cost.

In the two graphs below the table, can be seen that the main item is the clean-up system. It is very important to fuel cell technology, but at the same time it is also very expensive due to the high purity gas requested by the fuel cell modules. However, also the other items are too large. Anyway, they are after described and the motivation of their variation respect to the estimated cost too.

Showing results for the five macro-areas is propaedeutic to give an overview of costs related to those works. Nonetheless they do not provide any detailed information about SOFC modules, then about total DEMOSOFC plant cost. It is summarized in next table:

	Actual cost [€]
Site preparation cost	853.159
SOFC modules cost	3.037.989
DEMOSOFC cost	3.891.148

Table 2- Total DEMOSOFC cost

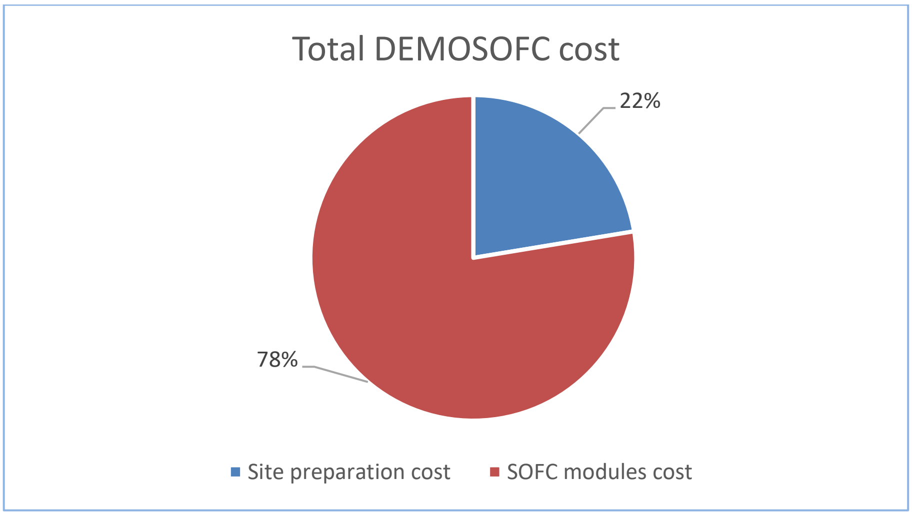


Figure 18- Total DEMOSOFC cost

Now it is possible to evaluate the plant cost referred to the plant size, as the following formula shows:

$$\frac{Plant\ actual\ cost}{Plant\ size} = \frac{3.891.989€}{174\ kWe} = 22.363\ \frac{€}{kWe}$$

Then, as shown before, approximately 4900€/kWe are caused by site preparation, then the other by SOFC modules. This result not only express the incidence of the fuel cell on the total cost, but it also represents an estimation of its actual huge cost.

After this plant overview, a deeper analysis is carried out through an appraisal of each of the above-mentioned works. This is done through a subdivision of each macro area into many categories and detection of costs related to them. Likewise, as it was done above, both a cost estimation in the design phase and actual costs occurred during the construction are reported with the related percentage variation.

Please note that the discount rate has not yet been considered to the following values.

3.2.1 Analysis on Mechanical Works

This work reports a cost reduction of 6.4% with respect to expectations. The selected categories belonging to it with their related costs follow in the table below.

	Estimated Cost [€]	**Actual Cost [€]**	**Cost Variation**
Primary heat recovery loop	36.371	32.532	-10,6%

Secondary heat recovery line	56.005	51.476	-8,1%
Sludge warming line	24.680	27.523	11,5%
Heating of Technical water line	5.016	3.396	-32,3%
Compressed air line	4.837	4.837	0,0%
Cost of labour	57.055	60.985	6,9%
Biogas and technical gases line	72.017	62.187	-13,6%
Additional works	29.732	20.489	-31,1%
Safety cost	3.667	6.495	77,1%

Table 3-Comparison between estimated and actual costs of mechanical works

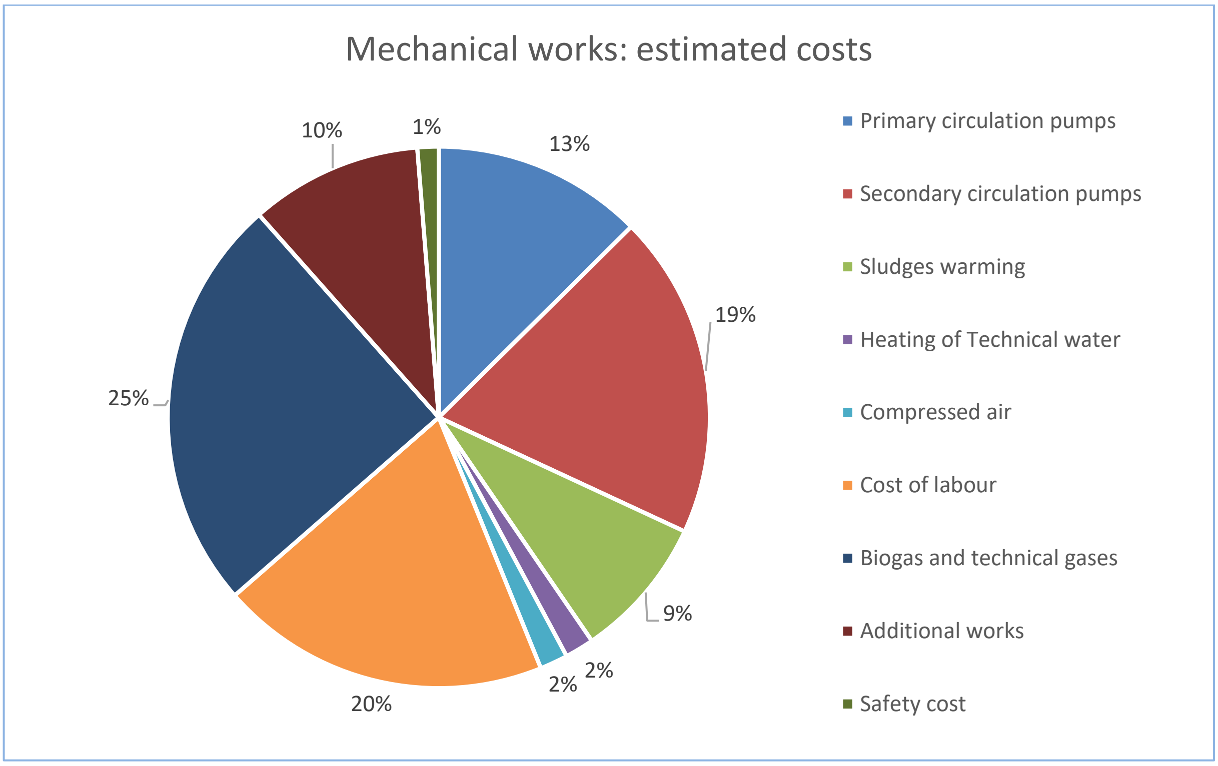


Figure 19-Relative weight of each item in the framework of estimated cost of the mechanical works

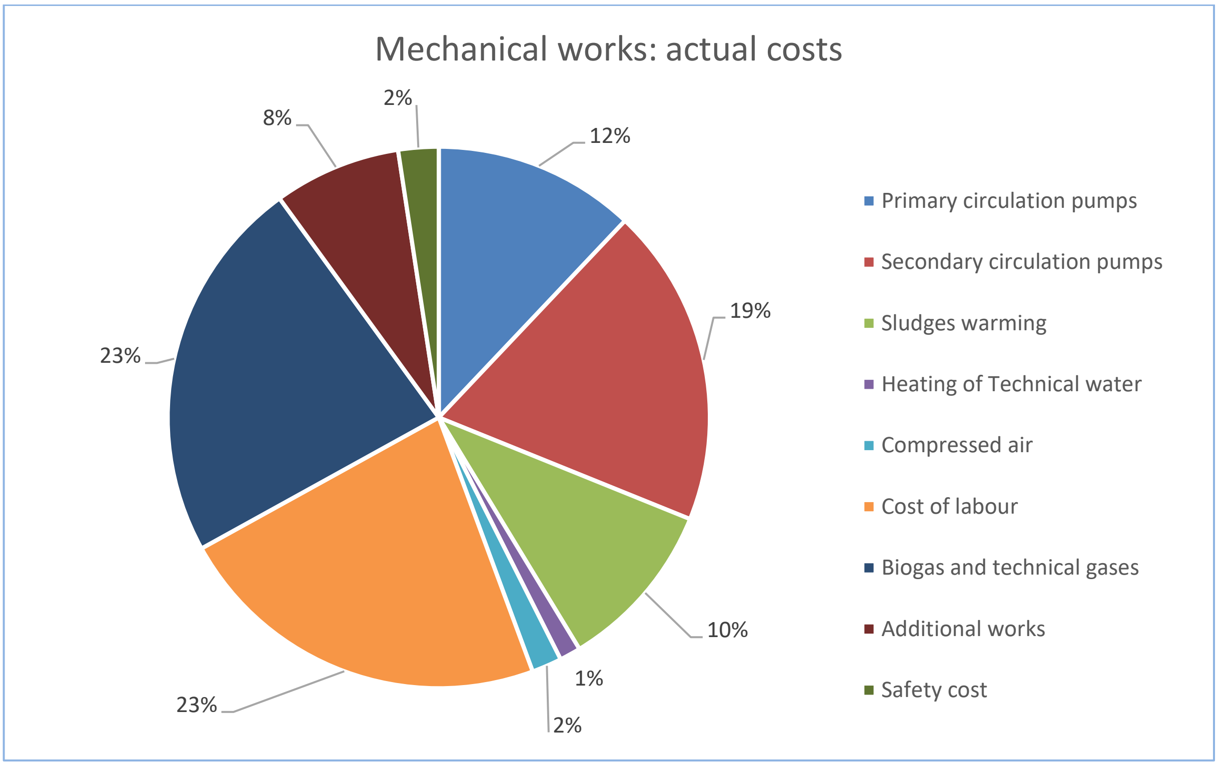


Figure 20-Relative weight of each item in the framework of actual cost of the mechanical works

Variation in mechanical cost is split among all the nine categories; almost all of them were underestimated in the design phase while others were overestimated. Except the safety cost, the positive increment is due to cost of labor that is boosted by 7%. All the others have a reduction of costs, due especially to the heating of technical water line installation, that mitigates the additional costs highlighted above and leads to an overall decrease of the final actual cost with respect to predictions.

3.2.2 Analysis on Electrical Works

This work reports a cost increase of 38.3%. Unlike it was done in the previous paragraph, it is not possible to evaluate a cost variation per each subsection because of the lack of some information. Therefore, only the estimated costs are reported below:

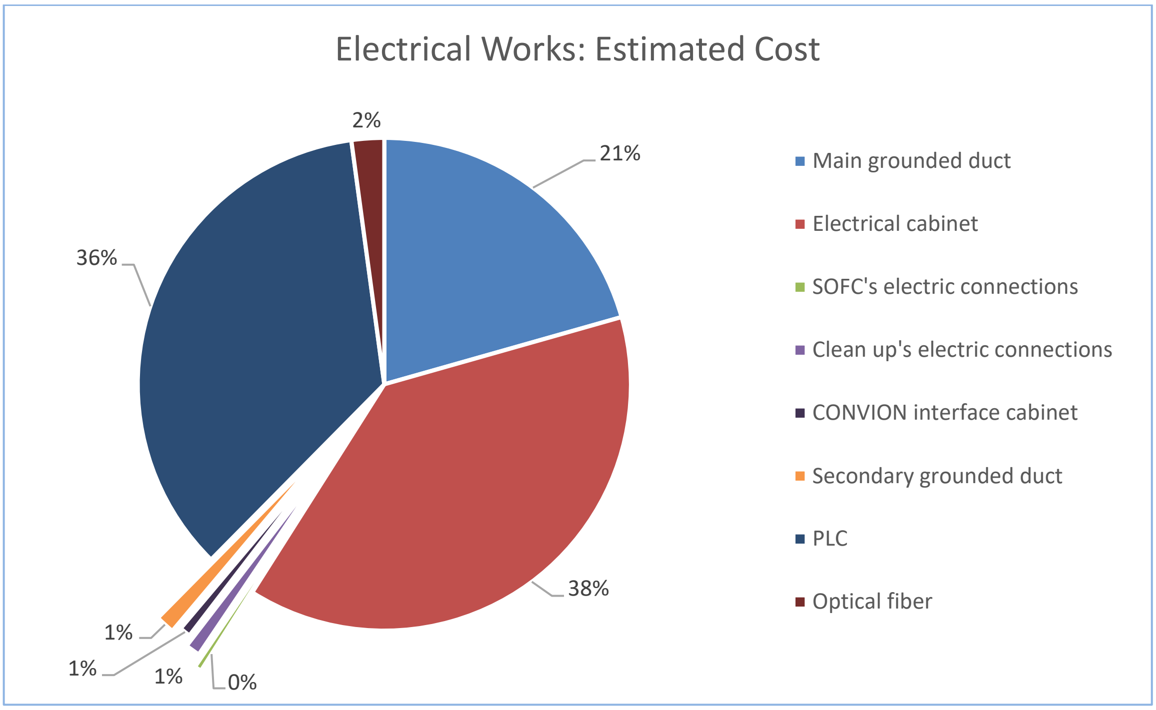


Figure 21-Relative weight of each item in the framework of estimated cost of the electrical works

Such a big gap between estimated and actual cost is due to the massive variations that occurred during the construction phase.

Given the estimations above, it is reasonable to suppose that the main additional expenditure is to be split among the following items:

- Grounded ducts;
- Electrical cabinet.

With regard to the first, a larger amount of site preparation and cables are required because of safety analysis. This is why it is reasonable to think that part of the increase is due to this item.

Furthermore, the need of additional components in the technical room and the different allocation of the UPS in another room, as well as an increase in battery's capability, makes reasonably suppose a bigger expenditure in the items concerning the electrical cabinet.

Last but not least a technical aspect is worth to be taken into account. Theoretically the Italian legislation does not allow a large increase in the construction phase costs in comparison to those estimated in the design phase. The maximum permitted is 20% which is nearly a half of variation incurred in this work. Such boost is mainly due to the fact that the construction of the MV cabinet is not taken into account since it is not a work which is strictly related to the DEMOSOFC project. Nonetheless this cost is considered both in design phase and construction one, accounting for 116’000€, then the surplus evaluated above would decrease to values accepted by law.

3.2.3 Analysis on Civil Works

Among all the works, civil ones are those with the largest increase of the actual cost if compared to the estimated one: +49%.

		Estimated Cost [€]	**Actual Cost [€]**	**Cost Variation**
Basement and technical building	Excavation and Earth moving	8.340	16.450	97%
	Demolition and removal	16.561	12.942	-22%
	Works in reinforced concrete	41.939	68.766	64%
	Metal framing works	17.788	33.205	87%
	Ducts, covering and floors	12.942	34.130	164%

	Frames and external cladding	31.156	47.643	53%
Pipe-Rack	Excavation and Earth moving	332	5.515	1564%
	Demolition and removal	795	7.674	865%
	Works in reinforced concrete	5.060	6.792	34%
	Metal framing works	41.413	51.712	25%
	Ducts, covering and floors	0	989	-

Table 4-Comparison between estimated and actual costs of electrical works

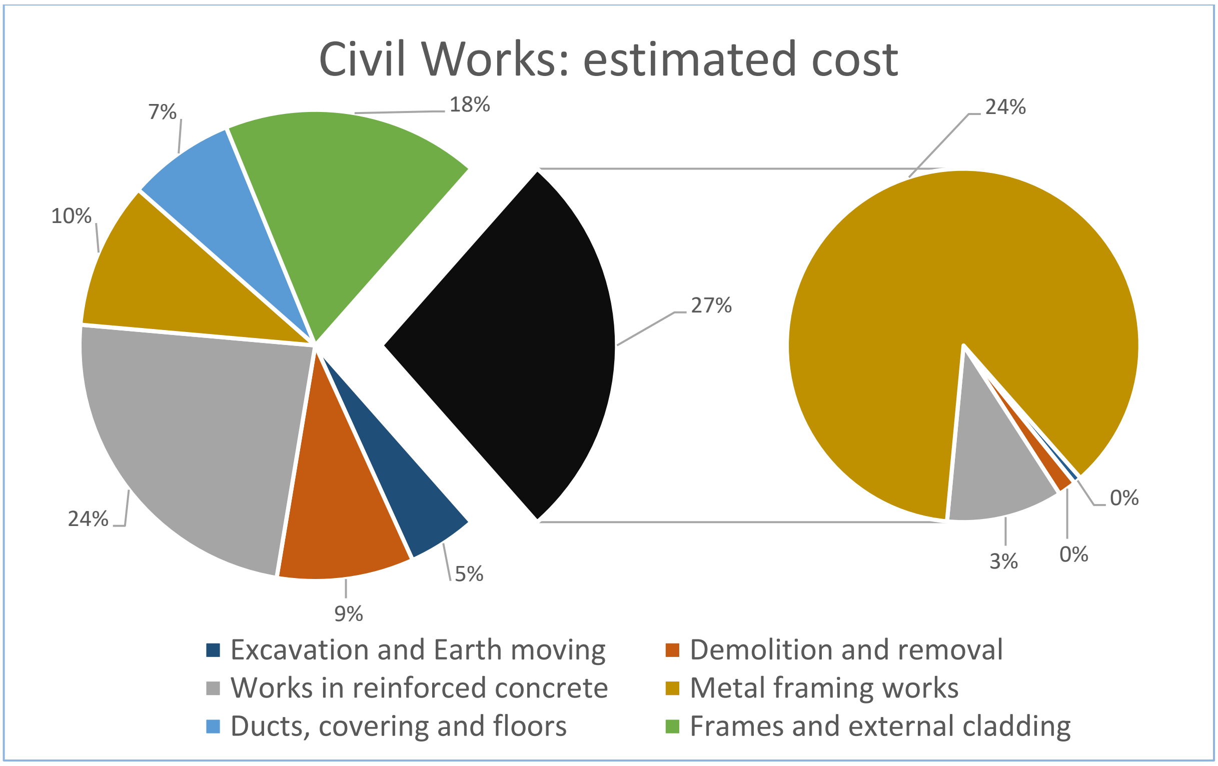


Figure 22-Relative weight of each item in the framework of estimated cost of the civil works

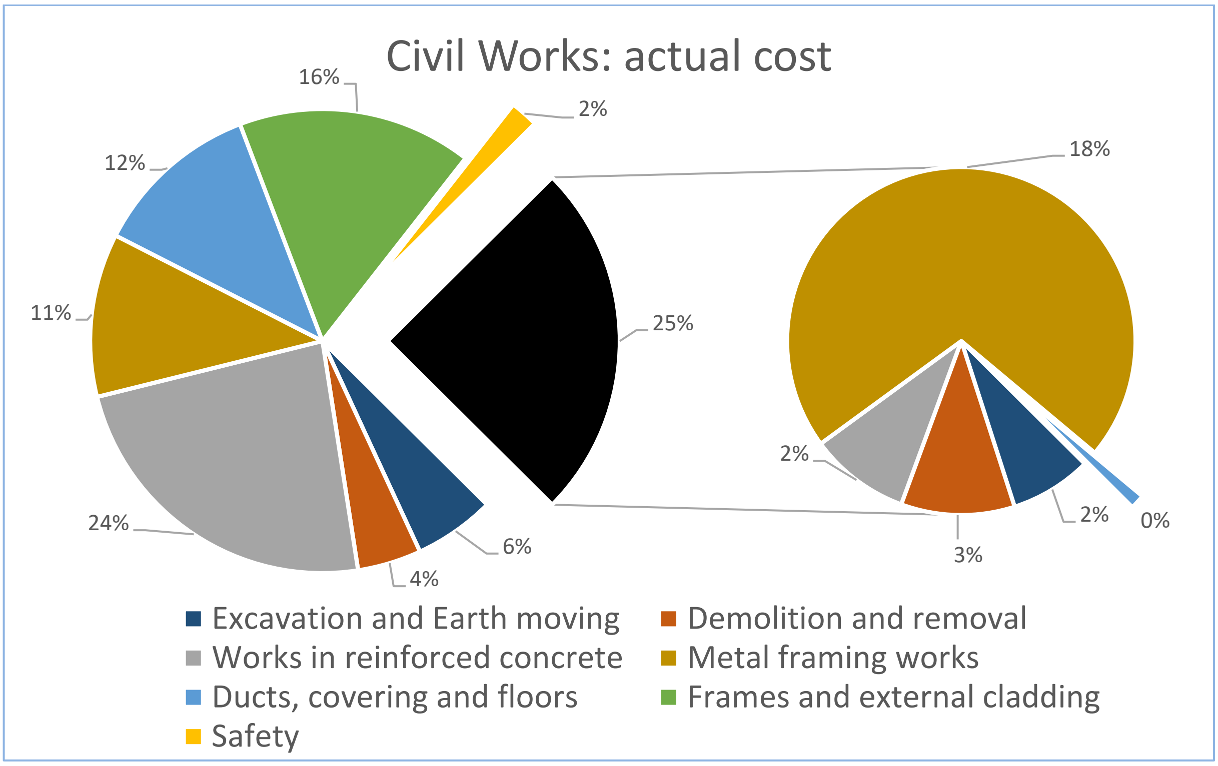


Figure 23-Relative weight of each item in the framework of actual cost of the civil works

The figures above try to highlight how costs related to items reported in the table above are divided in both basement and technical building (reported on the left hand side) and pipe-rack (on the right hand side).

The variation is mainly due to the following reasons:

- Modification of the layout of the plant. The risk analysis led to extension of the area built in reinforced concrete, of the ducts of both gas and electric lines and, last but not least, of the footpath around the technical building;
- Construction of additional structures for technical gases –i.e. N2 and NH mix;
- Adaptation of an already existing structure for the allocation of the UPS. Although it was initially thought to be placed in the technical building, some mistakes in the evaluation of its dimension were made. Consequently, it was moved to another existing room which had to be insulated and painted. On top of it all, an air conditioning had to be installed in order to keep the internal temperature of the structure constant;
- A higher amount of reinforced concrete was required for Bio-komp since the expected dimensions of its structure were much lower than the real ones.

- A higher amount of plinths of pipe rack was needed, which involved an increase of excavation costs, works in reinforced concrete and metal works too.

Once again, this variation meets the criteria of Italian legislation. Unlike the electrical works, the company in charge of maintenance service is the same as the one that worked for the installation. This leads to an allowed surplus in the actual costs up to +50% with respect to estimated ones.

3.2.4 Analysis on Clean-up System

Actual costs related to clean-up system meet expected ones since a slight variation accounting for 3% is obtained. Similarly to the electrical works, because of the lack of some information, only estimated costs are reported. Therefore, a general approach to the economic analysis is provided in this paragraph.

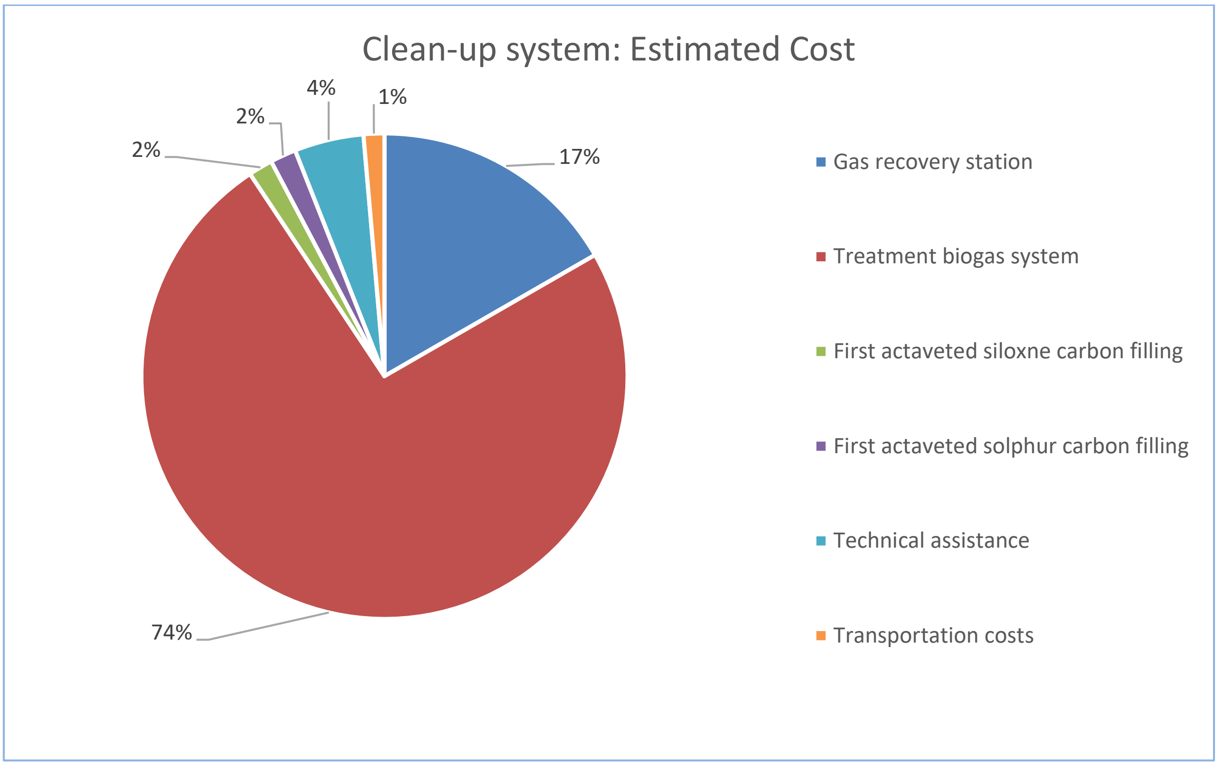


Figure 24-Relative weight of each item in the framework of estimated cost of the clean-up system

It is probable that the slight increase is due to a modification of the original layout through the addition of two one-meter long pipes due to the risk analysis.

It is therefore reasonable to suppose the cost distribution of the actual cost is like the one shown above.

3.2.5 Analysis on the Auxiliary Works

As clean-up system, a slight increase of 10% relative to auxiliary work is obtained too.

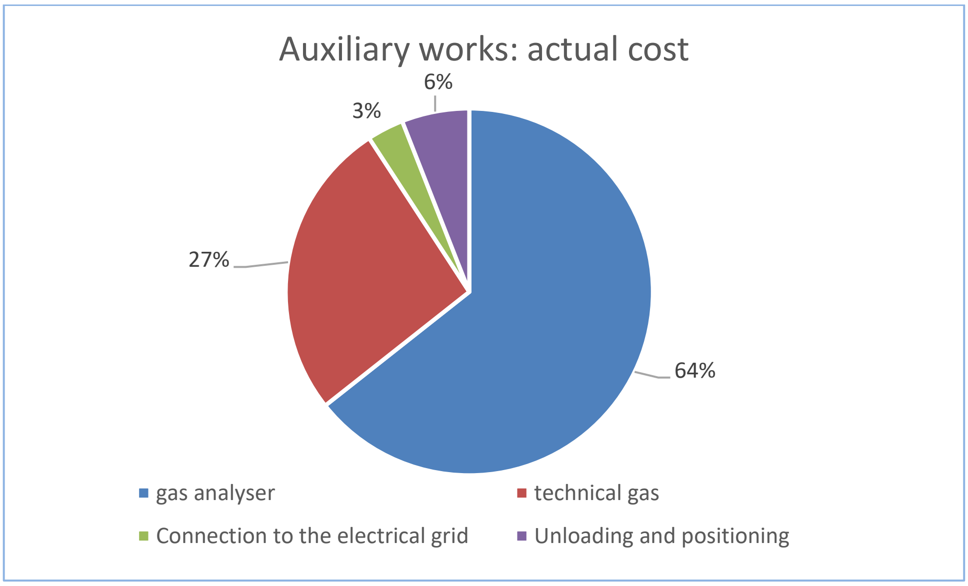


Figure 25-Relative weight of each item in the framework of estimated cost of the other works

It is caused mainly by the connection to the electrical grid works. In fact, it is not considered in design phase, but it is only added in the construction phase when network operator shows the necessity of a bidirectional counter.

4 Optimization plant design

From the cost analysis resulted that this plant is very expensive. In fact, an expenditure of 4.000.000€ to a plant of 174kW is too high. In order to estimate how much it is higher, in the following graph it is reported the trend of investment cost of a plant of biogas production which is used in an ICE, that is the standard technology [14]. Moreover, the trend of cost/power ratio of each size plant is shown, too.

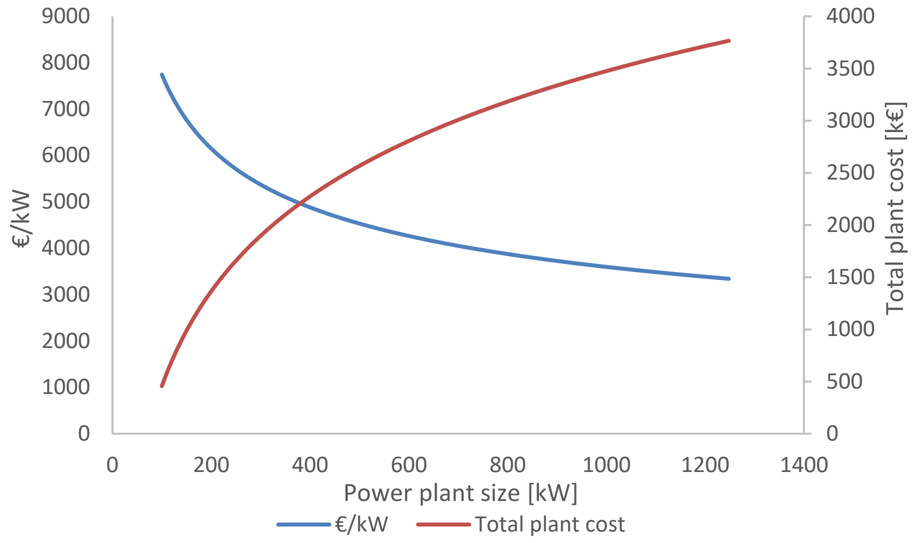
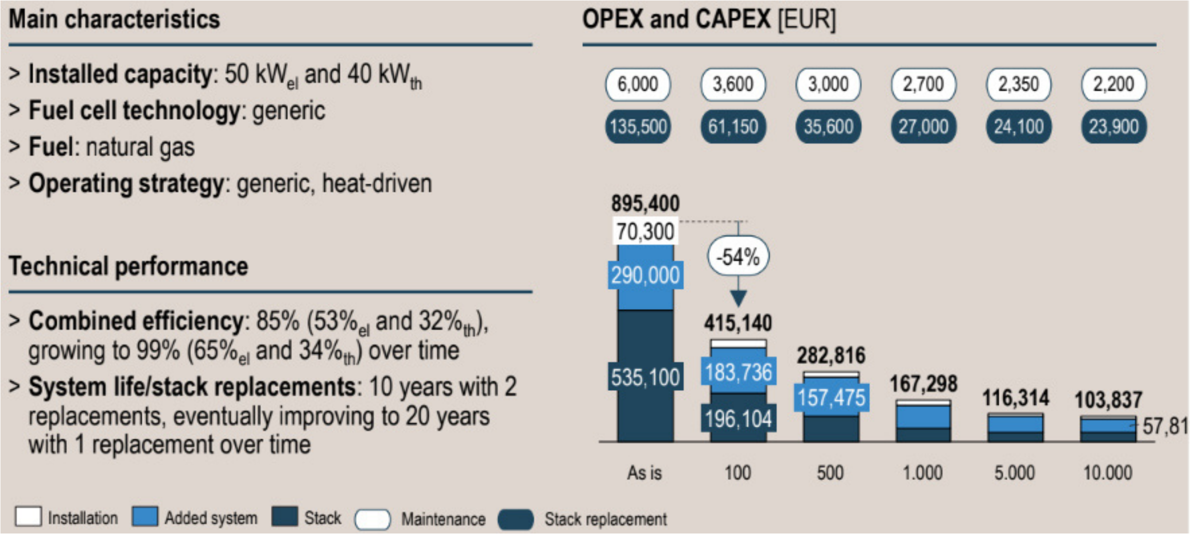


Figure 26-Investement plant cost using traditional technology

Then, from this graph it is possible to note that on equals terms of investment cost the plant size realized with traditional technology is approximately of 1250 kW. On the other hand, related cost/power ratio, the higher value is 8000 €/kW, that is so faraway from this specific case. Based on this consideration, a cost optimization of this plant is strictly necessary to promote the penetration in the market of the fuel cells, especially if it is considered that DEMOSOFC plant is only used to utilize biogas, on the contrary of studied traditional technology plants.

Back to DEMOSOFC plant, the higher cost it is due to SOFC modules. It is reasonable to explain, if it is considered that is a new technology. As all each new technology, at the beginning it has a very high cost due to financial reason, that is the lower demand than supply and the higher production cost due to mass production. Exactly for these reasons, it is also reasonable to think that fuel cells cost will have a large decrement in the future. In fact, a study demonstrates that the fuel cell cost might have the trend shown in the following figure [16]:


Main characteristics

- **Installed capacity**: 50 kW_{el} and 40 kW_{th}
- **Fuel cell technology**: generic
- **Fuel**: natural gas
- **Operating strategy**: generic, heat-driven

Technical performance

- **Combined efficiency**: 85% (53%$_{el}$ and 32%$_{th}$), growing to 99% (65%$_{el}$ and 34%$_{th}$) over time
- **System life/stack replacements**: 10 years with 2 replacements, eventually improving to 20 years with 1 replacement over time

Figure 27-Expected cost trend of a 50 kWe fuel cell

It shows a decrement of 69% in the middle term and one of 88% in the long term. It means that, starting from this analysed plant, the SOFC modules cost might approximately be either 950.000€ in the middle term scenario, or 350.000€ in the long term scenario. Then, if the site preparation cost remains equal to that evaluated in this case, it will be approximately equal to the fuel cells module or even higher, based on the considered scenario. In other words, utilizing the previous hypothesis and considering a long term scenario, the total plant cost will be approximately of 1.230.000€ that correspond to a 7.057 €/kWe. Related to the trend shown in figure 26, the considering scenario can be taken into account because the plant cost is similar to the traditional technology.

As a matter of fact this scenario doesn't make sense, as it refers to a value of 1.230.000€ that is as much as a fuel cell that has already penetrated the market. Therefore, to perform a correct analysis we have to suppose a more realistic hypothesis, that is a middle term scenario. From this point of view, the total plant cost will be approximately 1.830.000€ corresponding to 10.500 €/kWe. Again, in this new scenario, a higher cost respect to traditional technology one resulted. Anyway, it is easy to note that in this case the site preparation cost represents 48% of the total plant cost. It is not acceptable to a well-known technology. Finally, it is possible conclude that the only acceptable way is to redesign all the plant in order to try to reduce its cost.

4.1 Data reworking

To redesign the plant, it is important to understand what caused the huge plant cost. To do it, a data reworking is made. To do it, all realized works are reorganized in new macro areas. They are subdivided in three main type of works, that are strictly necessary to realize the plant. They are the ducts, the platform and the technical building. Moreover, in order to consider all works, another category is reported too, that is safety and other works. In this way all works, except the clean-up system, are taken into account.

This analysis is summarized in the next table:

Ducts		**Excavation**	**Work in reinforce concrete**	**Raw material cost (tubes, valves..)**	**Cost of labour**	**Total cost**
	Grounded ducts	€ 3.570	€ 21.896	€ 217.877	€ 65.533	€ 444.813
	Pipe racks	€ 14.766	€ 19.974	€ 54.100	?	
	Electrical ducts	€ 5.374	€ 0	€ 41.723	?	
	Sum	€ 23.710	€ 41.870	€ 313.701	€ 65.533	
Platform	**Excavation**	**Work in reinforce concrete**	**Platform to UPS**	**Platform to technical gas**		€ 36.680
	€ 11.983	€ 18.521	€ 3.377	€ 2.799		
Technical building	**Metal framing works**	**Technical building works**	**UPS building**	**Electric cabinet**		€ 212.292
	€ 33.070	€ 46.623	€ 9.174	€ 123.426		
Safety and auxiliary works	**Safety cost and auxiliary works**	**Gas analyser**	**Technical gases**	**Electrical grid connection**	**Unloading and position**	€ 129.295
	€ 37.618	€ 59.000	€ 24.258	€ 2.958	€ 5.461	

Table 5-Reworking data about necessary works

By this new reworking data, it is possible to take same observation. First of all, the cost of ducts is approximately an half of the total plant. In this subsection, the largest part is due to the grounded ducts. However, a big quantity (approximately 90.000€) is due to pipe racks, that is a specific necessity of the Collegno plant.

The second that have higher value is the technical building. Although its cost is due mainly to electric cabinet, an expenditure of approximately 90.000€ to its construction is too high.

Then, there is the cost of safety and auxiliary works, where the cost of gas analyser is the most of it. However, almost all auxiliary works are actually unnecessary as wall as technical gases, due to its overestimation.

Finally, there is the platform cost, that is almost negligible compared with the other.

4.2 Redesign hypotheses

The plant redesign aims at evaluating the base case plant, that is the minimum investment cost that is needed to realize this kind of plant. To perform it, some hypotheses are needed that are based on the previous analysis. The aim of this paragraph is to explain them and reasoning where they come from.

In order to have the minimum cost, the first and main hypothesis made concerning the choice of taking into account only the works strictly necessary of DEMOSOFC plant. It means that all the works specific to Collegno plant have not been considered, otherwise, from a replicability point of view, the final result is distorted. In other words, a control volume on DEMOSOFC area is imposed. It is important to stress on the power of this hypothesis: thanks to it, the whole pipeline that connect the existing area with the DEMOSOFC one has not been considered. In fact, in another plant this distance can be either smaller or larger, then, a general consideration of this plant, it is not taken into account because it depends strictly on the considered plant. Furthermore, in a new realized plant, this distance will be certainly optimized in order to be as low as possible.

Another important hypothesis is the use of one SOFC module of 175kW instead of three module 58kW each. This choice can be explained considering that the market fuel cells' trend is oriented to the larger size modules. In this way, a reduction of pipeline is expected.

Remaining on the category of the ducts, another hypothesis is made. Due to the high expenditure of excavation and works in reinforced concrete regarding to underground ducts, it has been thought to let them pass over the platform. Obviously, in this way, each line has to pass through cable ducts.

As to the technical building, its cost is approximately subdivided into electrical cabinet and technical building construction. Regarding the first, it is strictly needed in order to manage the plant and, since it is a little oversized, it is kept equal to the used one. Instead, regarding its construction it is supposed to use a container. In this way, it is possible to have a large reduction due to the raw material cost, but it is especially due to the vary large reduction of labour cost and safety cost. In fact, in this way, the plant is smarter, and faster to realize.

Regarding the safety and auxiliary works, they can be reduced almost all. In fact, the considered safety cost also includes chemical bath and the office container used in the building sites. However, with the optimization design a reduction of the duration of works is expected, then safety cost will be reduced. In the item 'auxiliary works' many works that are not strictly necessary to DEMOSOFC are included, then they are not considered in this optimization. The gas analyser is oversize, in fact it was chosen for study purpose, but a more economic one is just as good. About technical gases, by the accumulate experience they resulted oversized. Furthermore, they will be moved near fuel cell module and near the clean-up container obtaining a reduction of its pipelines. They are not explosive and not inflammable gas, then it is approved by safety analysis point of view.

Finally, the lead&lag configuration in the clean-up system will be removed. In fact, it was chosen in order to avoid the stop of the plant when it is necessary the replacement of activated carbon catalyst. Nevertheless, by experience, in these cases the plant was stopped anyway, making this configuration unnecessary. In this way, the clean-up system doesn't have an expensive technology, and a reduction of tank and activated carbon is performed. Moreover, it also means a reduction of container dimension, that is a reduction of occupied area on the platform.

Then, these hypotheses are following summarized:

- Control volume on DEMOSOFC area
- Only one 175kWe fuel cell module
- Use of cable ducts
- Container for technical building
- No lead&lag configuration

The works that will be applied, are furtherly described in the next paragraph.

4.3 Deeper description of each work and Results

Each kind of work following described is based on the realized work, in order to have the same quality and security. Then, not to repeat already described procedures, this description will focus on the changes that there will be.

4.3.1 Civil Works

Also in the optimized scenario, the necessary civil works which must be performed are the same of real one, that is the construction of:

- The reinforce concrete basement
- the technical building
- pipe racks and ducts

Obviously, some modification will be actuated.

The technical building will be not built in construction phase, but prefabricated container will be installed. In order to allocate all the components about electrical cabinet, a 6m long container is chosen.

The reinforce concrete basement must be able to host on itself the container of technical building, the container of clean-up system and the SOFC module. Respect to the actual case, these last two will change. In fact, how will be after explained, the container of clean-up system will be reduced from a 10m long to a 6m long. Instead, concerning fuel cell module, it is replaced by only one module, then it will be larger than one actual module. However, the expectation is that occupied area will remain approximately the same now occupied. Then, considering all the three compounds, an 10m x 13m rectangular basement will be performed. Also in this case, to realize the basement, excavation, formwork and the armours are needed. However, on the contrary of the realized case, now the excavation will be lower. In fact, due to the ducts are let them pass over the platform, it will be only of 30cm. In conclusion the reinforce concrete basement will be with rectangular shape with dimension of 10m and 13m and a thickness of 30cm.

Although the application of control volume on DEMOSOFC area, a small pipe racks must be anyway included. In fact, in any case DEMOSOFC area will be a certain distance from gas holder. In a general way, in this analysis is only considered the construction of two plinths. This choice does not mean that in any plants will need exactly two plinths, but it means that, according to control volume hypothesis, are considering only the two plinths inside this control volume able to connect DEMOSOFC area with the remain pipe racks. Once pipe racks link the gas holder with platform, in order to feed clean-up system and SOFC module, a pipeline is needed. In the optimized case, it must be pass on platform, then it is put in the cable ducts. Considering the estimation obtained in the analysis on the mechanical works, that is explained in the next section, 65m of cable ducts are considered. To establish its price (as well as to establish container price), a market research was performed. It takes place considering at least two different companies for each product and the highest price is taken into account in order to realize an estimate for excess. This price must be overestimated of 23% to take into account the market research cost and business profit. In the following figures, are shown, respectively, the kind of gas line ducts and the kind of 6m container that are chosen.

Figure 28-Cable duct to gas pipeline

Figure 29-6m long container

In conclusion, performing the works described in the optimized case, a drastically reduction of labour cost and safety cost are expected. In fact, to perform all these works it has been considered a period of three months, that is lower and lower respect to twelve months actually needed. Although it seems a huge reduction, it is a good approximation because few time is needed to install cable ducts and the container, while almost all the time is used to perform the platform and the two plinths.

4.3.1.1 Civil Works: Results and Cost variation

In the following table the estimated cost in optimized case and cost variation respect to the actual one are shown:

		Actual	**Estimated**	**Variation**
Basement and technical building	Excavation and Earth moving	€ 16.450	€ 2.345	-86%
	Demolition and removal	€ 12.942	€ 0	-100%

	Works in reinforced concrete	€ 68.766	€ 12.472	-82%
	Metal framing works	€ 33.205	€ 4.305	-87%
	Ducts, covering and floors	€ 34.130	€ 11.213	-67%
	Frames and external cladding	€ 47.643	€ 0	-100%
Pipe-Rack	Excavation and Earth moving	€ 5.515	€ 52	-99%
	Demolition and removal	€ 7.674	€ 0	-100%
	Works in reinforced concrete	€ 6.792	€ 776	-89%
	Metal framing works	€ 51.712	€ 2.646	-95%
	Ducts, covering and floors	€ 989	€ 0	-100%
	safety	€ 5.756	€ 1.782	-69%

Table 6- Estimated cost of Civil works and its comparison with actual ones

As seen in the analysis about actual cost, also in this case the figure below try to highlight how costs related to items reported in the table above are divided in both basement and technical building (reported on the left hand side) and pipe-rack (on the right hand side).

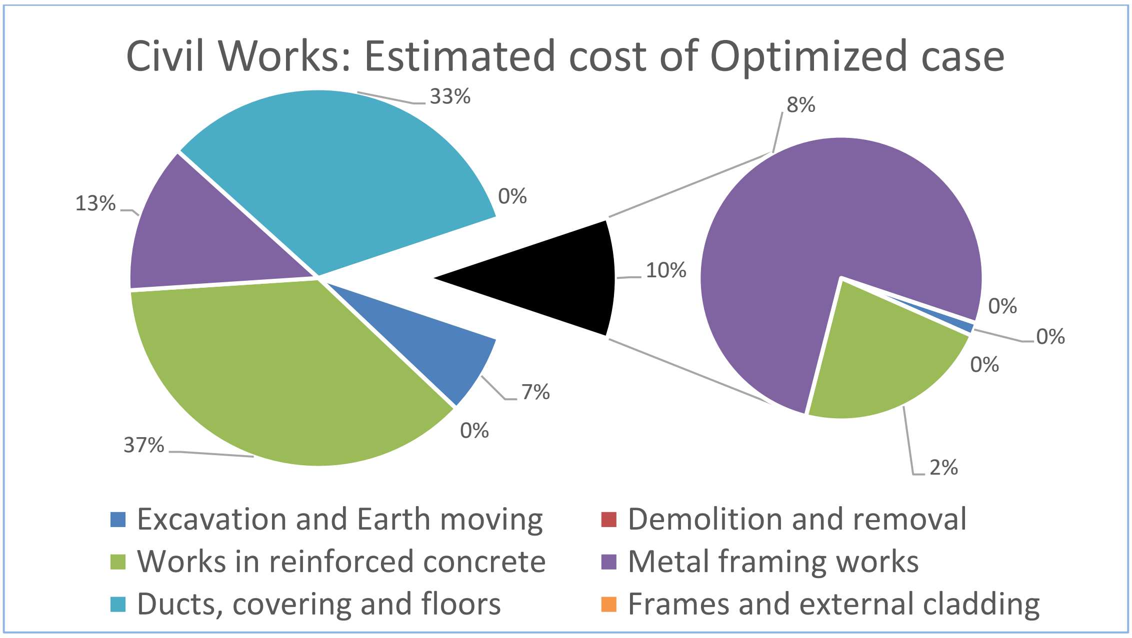


Figure 30-Relative weight of each item in the framework of estimated cost of the civil works

The table shows that each item is reduced from 67% to 99%. Then, these huge reductions demonstrate the powerful of the made hypotheses.

By the graph is possible to understand that the cost necessary to realize the starting part of pipe racks is only 10% of the total cost, while in the actual cost it was 25%, as it is shown in figure collegamento. Its higher part is due to metal framing needed to realize double T-shaped steel profiles. On the other hand, the cost of the technical building is 13% of the total one and the remaining part concerning the reinforce concrete basement. In this last item, although the made hypothesis, the cost of the ducts occupied a large part, but it is anyway reduced a lot respect to actual cost.

4.3.2 Mechanical Works

With the hypothesis of the control volume, in the optimized case the pipelines about secondary circulation pumps, sludge warming and heating of technical water are not included. Then, only the works concerning the pipelines of primary circulation pumps, compressed air and biogas and technical gases and the auxiliary works are performed. Obviously, in the cost analysis also the cost of labour and safety cost are included. The considered pipelines are simplified in order to include only the actual necessary components. To perform this simplification, the Piping and Instrumentation Diagram (P&ID) is used as reference. In fact, starting from actual P&ID, all the valves, the tubes and the measurement tools are evaluated and only the actually necessary of them are chosen. The not considered parts are highlighted with a red X above. Due to its huge dimension, following only the focus on the analysed part is shown.

In the next figure, the not included parts due to control volume hypothesis are shown.

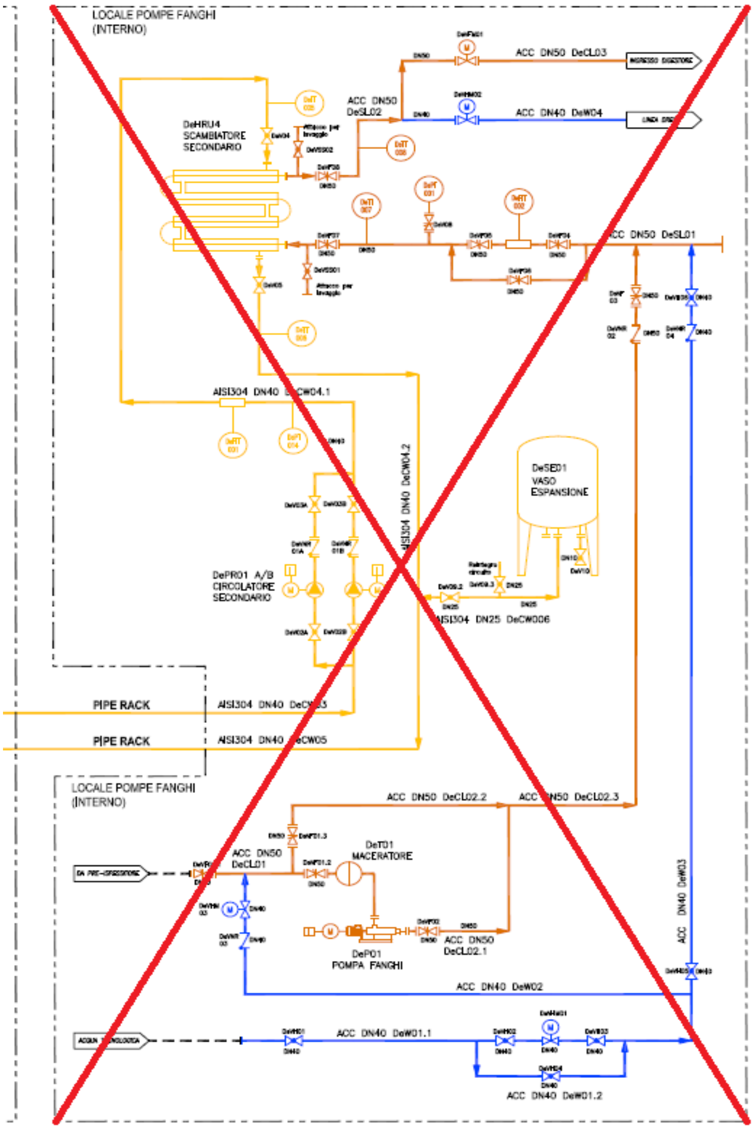


Figure 31-The excluded part concerning the secondary circulation pumps, sludge warming and heating of technical water

As can be seen, this is a very huge part. However, since it is only one application on the all existing, it is considered independent from DEMOSOFC area and then it is excluded. Anyway, from reduction cost point of view, the control volume hypothesis has proven its above mentioned powerful.

Another important made hypothesis regarding the use of only one SOFC module. As before, the reduction of P&ID due to this hypothesis is shown in the figure below:

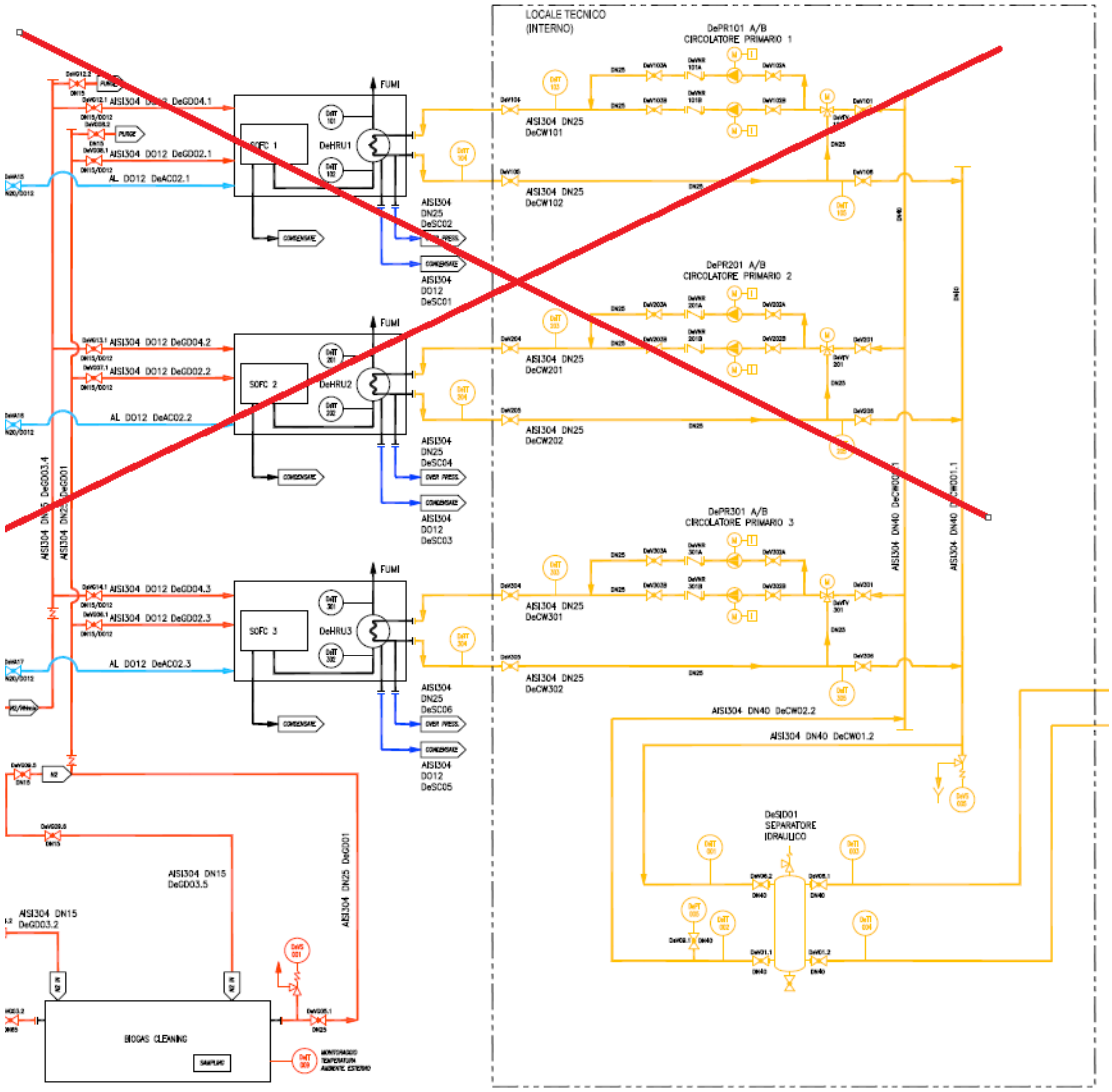


Figure 32- Reduction of components due from three SOFC modules to one module

As can be seen this hypothesis permits to have an important reduction on tubes, valves ad measurement tools. In fact, now there are three equal parallel lines, while, in the optimized case, there will be only one. In this way a reduction of one third of the components concerning the primary circulation loop line, compressed air line and biogas e technical gas line near the SOFC module is performed.

Hydraulic separator is kept because its aim is mixing cool water and hot water in order to keep constant the difference of temperature on the heat exchanger.

Finally, another simplification is made on the primary circulation loop, as can been seen in the next figure. It consists on removing the parallel line that fed the heat exchanger inside fuel cell module. It has been used in order to increase the availability of the plant and avoid unwanted stop of heat recovery unit, because in these cases it must be replaced by existing boiler natural gas fed. However, stop of the main line is a rare event, then in the minimum cost case the auxiliary line can be avoided.

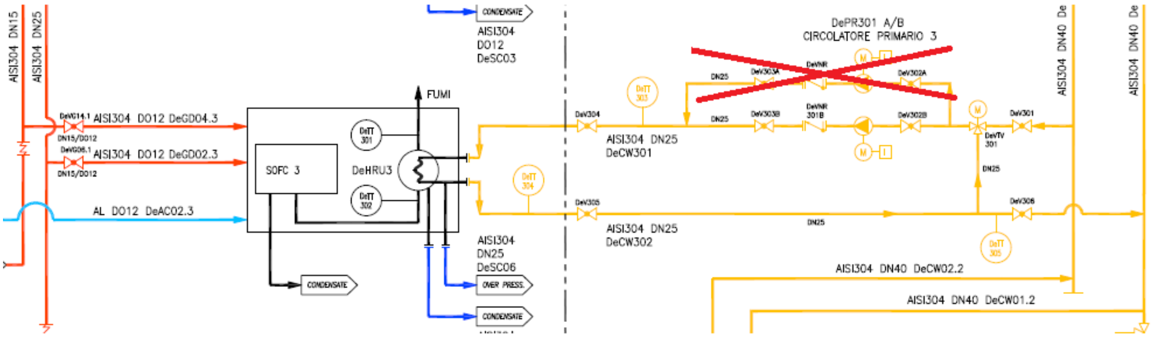


Figure 33-Exclusion of the parallel line fed HE inside the fuel cell

The compressed air line is now linked with the existing one. Then, also in this case a pipeline able to connect the existing area with DEMOSOFC one is needed. However, thanks to the control volume hypothesis this effort is not considered in the optimized case. Also in this case, it is represented in the following figure that shown a focus of P&ID:

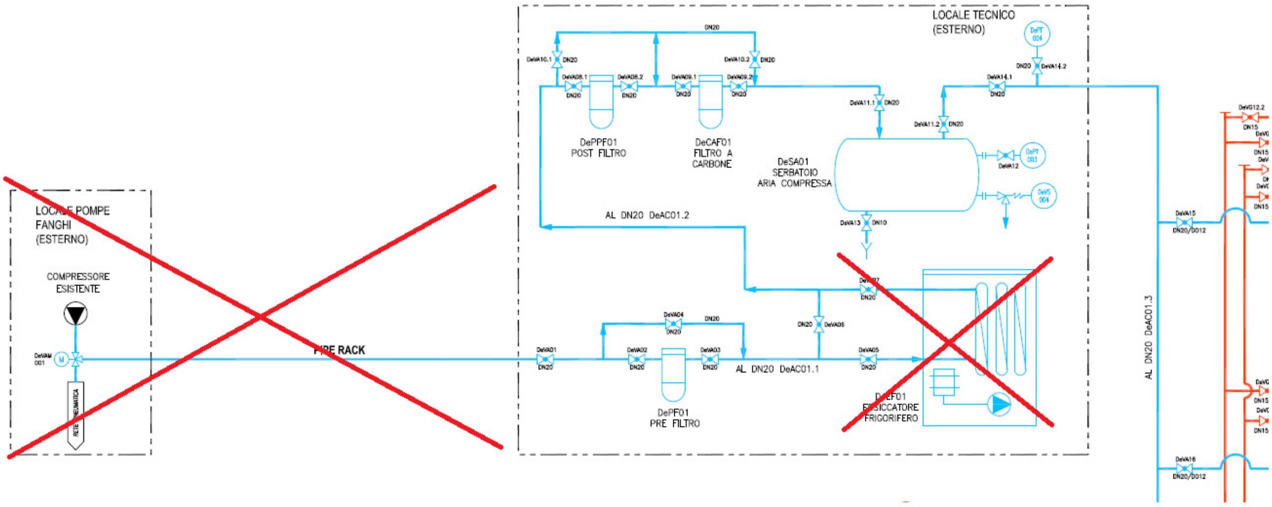


Figure 34-Reduction on the compressed air pipeline

Furthermore, as can be seen, also refrigerator dryer is eliminated. In fact it is assumed as non essential component, since generally each plant have already a dry air line. In other words, it is seen as a specific component of Collegno plant, the in base case it can be not considered.

The same applies to the gas pipeline and all involved components used to feed clean-up system, as can be seen in figure below:

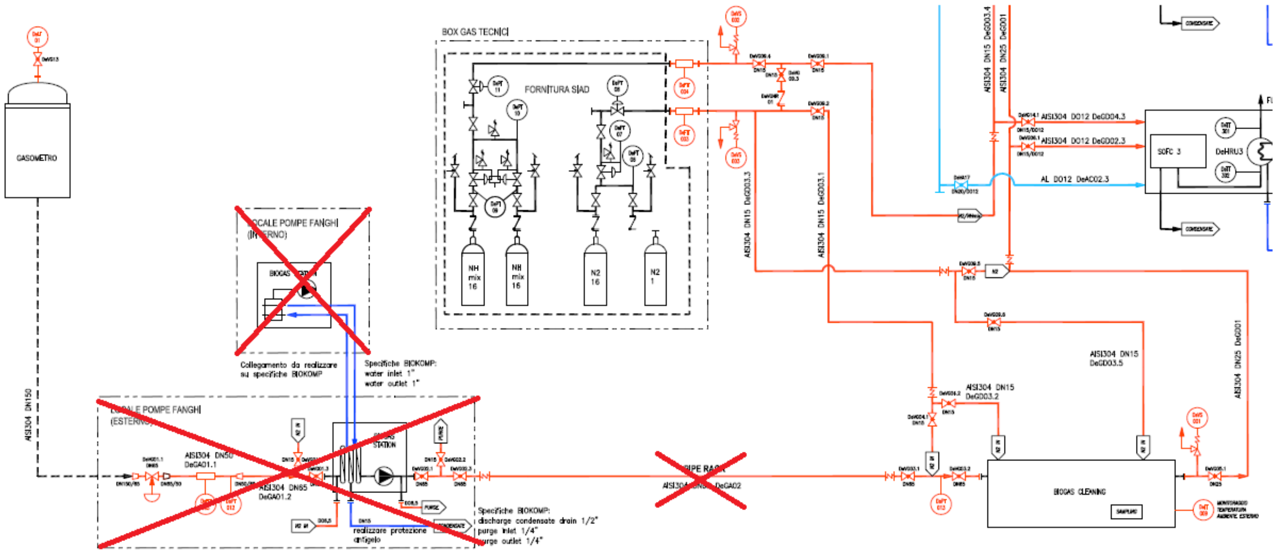


Figure 35-Reduction on the biogas pipeline from existing area to DEMOSOFC one

The last part concerning the pipeline to technical gases. Before they are placed in them box and linked to clean-up system and SOFC modules through a pipeline. Instead, in the scenario each gas battles are located near the fed components. Then, in this case that pipeline is not necessary.

Once it has been evaluated the quantity of valves and measurement tools utilizing the P&ID, the remaining part consist on evaluated the dimension of the tubes needed. They are supposed considering the control volume hypothesis and the dimensions of the platform (10m x 13m). Then it is estimated the following dimension:

- 15m to inlet/outlet heat recovery line
- 20m to compressed air line
- 30m to biogas line (both from plinths to clean-up system and from it to SOFC module)

Than a total of 65m tubes are needed.

Finally, to connect each other tubes, valves, measurement tools and component, they are needed curves, junctions, nuts and washers. Anyway, they are impossible to establish a priori, because depend on the configuration and disposition used. Then, to evaluate them an hypothesis on the actual design is performed: thanks to the SALs the quantity of above mentioned elements are well known, then to solve the problem it needs to choice a good percentage of these elements. To calculate it three parameters are evaluated: the cost of the tube of all pipelines in the actual case (Actually Completed or AC), the cost of the tubes of all pipelines kept in optimized case (biogas line, compressed air line, heat recovery line) in the actually case (Actually Not Completed or ANC) and the previous cost but referred to optimized case (Optimized or Opt). By these three parameters, two ratios are calculated, that is the ratio between AC and Opt and that between ANC and Opt. They represent the percentage of the necessary works kept in the optimized case respect to the actual works. In other words, they are the upper and lower limits that can assume the actually necessary works respect to the real used ones. In conclusion, the mean of these two ratios represent the researched good approximation of the percentage of the needed curves, junctions, nuts and washers.

This reasoning, and the relative results, is shown in the table below:

AC	Actually Completed	€ 150.844		Opt/AC rateo	30,82%
ANC	Actually Not Completed	€ 80.657		Opt/ANC rateo	57,64%
Opt	Optimized	€ 46.489		**Mean value**	**44,23%**

Table 7-Calculation to evaluate the value which is used to calculate the connection components

Finally, using this percentage to evaluate the number of each component a non-integer value is obtained, which has been approximated to the nearest upper integer in order to obtain an overestimation.

4.3.2.1 Mechanical Works: Results and Cost variation

In the following table the estimated cost in optimized case and cost variation respect to the actual one are shown:

	Actual	Estimated	Variation
Primary circulation pumps	€ 32.532	€ 17.611	-46%
Secondary circulation pumps	€ 51.476	€ 0	-100%
Sludges warming	€ 27.523	€ 0	-100%
Heating of Technical water	€ 3.396	€ 0	-100%
Compressed air	€ 4.837	€ 4.009	-17%
Cost of labour	€ 60.985	€ 24.840	-59%
Biogas and technical gases	€ 62.187	€ 43.386	-30%
Additional works	€ 20.489	€ 7.395	-64%
Safety cost	€ 6.495	€ 5.153	-21%

Table 8-Estimated cost of Mechanical works and its comparison with actual ones

As seen in the analysis about actual cost, also in this case the figure below tries to highlight how costs related to items reported in the table above.

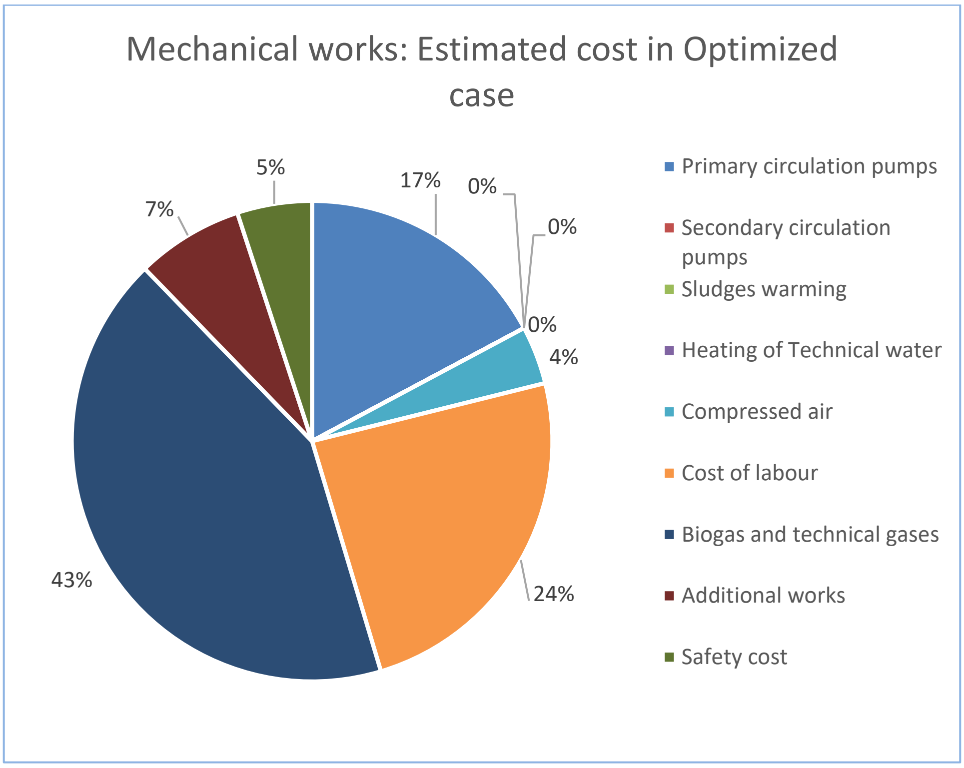


Figure 36-Relative weight of each item in the framework of actual cost of the mechanical works

Also in this case, the table shows that each item have a reduction. However, the variations regarding mechanical works are lower respect to civil works. In fact, they vary between a reduction of 17% to

64%. Although they are small, they are all reductions, then they demonstrate that has been chosen good hypotheses.

On the other hand, the graph shows that, in the optimized case, the largest item is about biogas and technical gases. Although the huge reduction on its pipeline, it is almost high mainly due to the huge cost of the measurement tools. They are necessary in order to guarantee the good operation of the system and to increase its availability, but they cover over the 50% of the biogas and technical gases cost.

The other main items are the labour cost and the primary circulation pumps. The first can explained considering the need time to assembly all the components, instead the second can be explained considering that, as it is seen to biogas and technical gases line, the pump cost and measurement tools cover approximately the 60% of its total cost.

4.3.3 Electrical Works

About electrical works few modifications are performed. In fact, thanks again the control volume hypothesis, they concerning mainly the reduction of the electrical cables that has been installed to connect each other the two areas. In fact, in the optimized case only the electrical connection from technical building to clean-up system and SOFC module, as wall as to each control system, are considered. To perform these connections, 50m between technical building and SOFC module and 30m between the first with the clean-up system are considered. Moreover, also in this case excavation is not necessary because grounded ducts are replaced by cable ducts and also in this case their cost has been evaluated through a market research, as well seen in the civil works. The kind of cable duct chosen is shown in the next figure. This decision is taken because it lest air pass through and then it can cool down the cables, heated by Joule effect.

Figure 37-Cable duct to electrical connections

However, from a conceptual point of view, the main modification concerning the UPS. Although the rest of electrical cabinet is kept equal in order to not reduce its high quality, the UPS has been reduced. This choice is due to its higher overestimation. The UPS is necessary to switch from normal operation to island mode, which is used when black out occurs. It consists in using only the electrical power generated by fuel cell to feed all the auxiliary process of DEMOSOFC plant. In this way, it is possible to continue the gas supply and avoid unwanted plant shut-down and to avoid the cooling down of fuel cell's module, that can damage it. UPS is the ideal instrument to perform this specific task: when black out occur, it is able to switch from grid fed electrical power supply to its battery fed one. Once it keeps on all the auxiliary components and the fuel cell is able to feed these components through its electrical power produced, the UPS switch again from its battery fed to fuel cell fed. This happens in few seconds. Really, at state of the art, all that previously described happens in less than one second. However, the batteries of UPS are able to feed the auxiliary components to 30 minutes, then, as above mentioned, they are oversized. To this reason, in this optimized case their capacity is drastically reduced, although keeping a good safety margin.

4.3.3.1 Electrical Works: Results

As mentioned when the analysis on the actual costs is described, that referred to electrical works is missing. Then, on the contrary to what was done before, in this case is not possible perform a cost variation respect to the actual cost. However, the estimated costs of optimized case referred to each item, are shown previously in the following table and then in the next figure.

	Estimated cost
MV/LV cabin	€ 0
Main grounded duct	€ 0
Electrical cabinet	€ 50.270
SOFC's electric connections	€ 4.354
Clean up's electric connections	€ 2.094
CONVION interface cabinet	€ 0
Secondary grounded duct	€ 0
PLC	€ 58.364
Optical fibre	€ 0

Table 9-Estimated cost of Electrical works

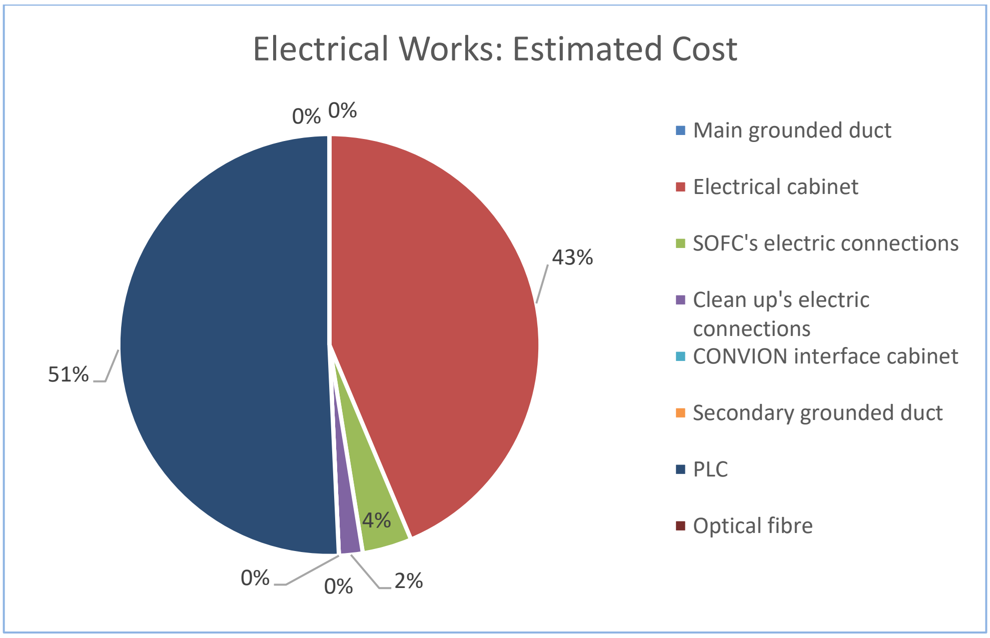


Figure 38-Relative weight of each item in the framework of estimated cost of the Electrical works

From them, it is evident that almost all the cost is due to proper cost of two components and their installation cost. That is reasonable considering that these two components are the PLC and the electrical cabinet, that represent the crux of the electrical works.

4.3.4 Clean-up system works

As already described before, in this section lead&lag configuration will be removed. This decision causes a reduction of tube and valves, as well as of the numbers of tanks. This last reduction causes a reduction of activated carbons catalyst. These components represent the core of the clean-up system, because is the place in winch the gas is effectively cleaned. Then a huge reduction on this system is expected.

4.3.4.1 Clean-up system: Results

As well the Electrical works, also in this case it is not possible make a comparison between actual cost and this estimated one for the same reasons. However, it is also possible highlights how costs related to each item are subdivided, thanks to the following figure:

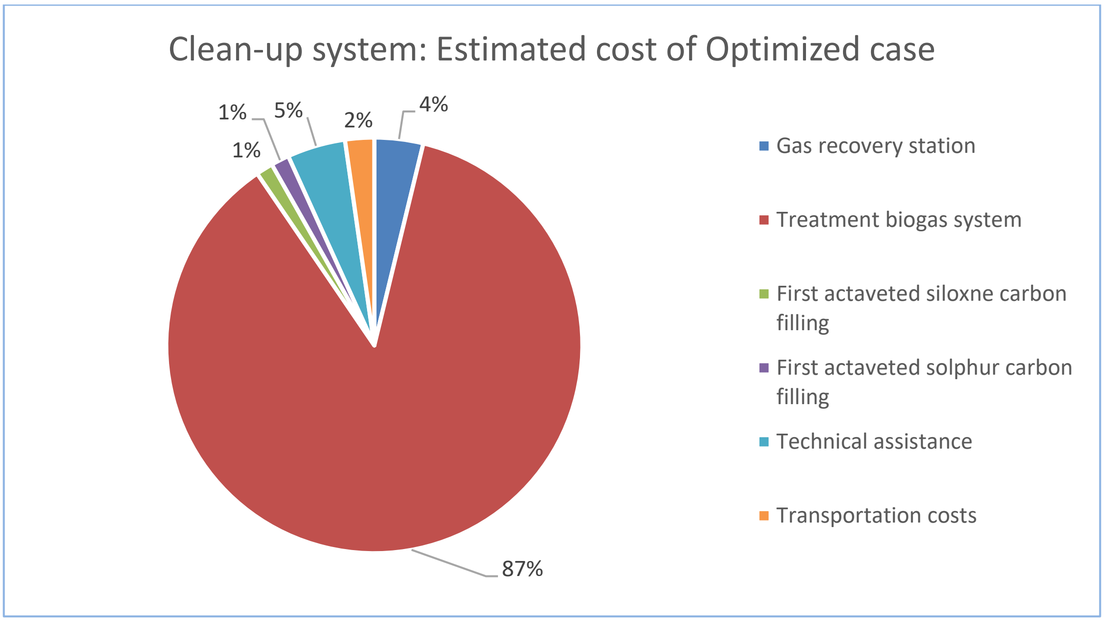


Figure 39-Relative weight of each item in the framework of estimated cost of the clean-up system

As can be seen, although its simplification, approximately the total cost is due to the treatment biogas system. That is reasonable considering that it is the core of this system.

4.3.5 Auxiliary works

In the item auxiliary works are included all the works and auxiliary components that can not be included in the other categories. Then here there are the gas analyzer, technical gases, connection to the grid and unloading and positioning cost. This last two item are approximately the same in both scenarios, because the installed power is the same then it is reasonable thing that also the costs related to the connection is approximately the same. On the other hand, the cost of unloading and positioning can be assumed approximately the same because in current scenario has been necessary unload the clean-up system and three SOFC module, while in the optimized scenario might be unloaded one SOFC module, one container to clean-up system and one container to technical building. They are similar, in particular if dimensions of the container are took into account. Then its cost is kept constant.

Instead the other items are decreased. Concerning gas analyzer, it is reduced because has been chosen one cheaper that not have a very high accuracy and not have some functions respect the actually utilized. Also in this case, as explained in the civil works, a market research has been performed to evaluate its cost.

On the other hand, the number of the technical gas cylinders is reduced because actually are oversized. In the current scenario are placed two gas cylinders of all kinds near the fed system. Then totally eight gas cylinders are installed.

4.3.4.1 Auxiliary works: Results and Cost variation

As before, in the following table the estimated cost in optimized case and cost variation respect to the actual one are shown:

	Actual	Estimated	Variation
gas analyser	€ 59.000	€ 31.000	-47%
technical gas	€ 24.258	€ 15.178	-37%
Connection to the electrical grid	€ 2.958	€ 2.958	0%
Unloading and positioning	€ 5.461	€ 5.461	0%

Table 10-Estimated cost of Auxiliary works and its comparison with actual ones

Instead, the figure below tries to highlight how costs related to items reported in the table above.

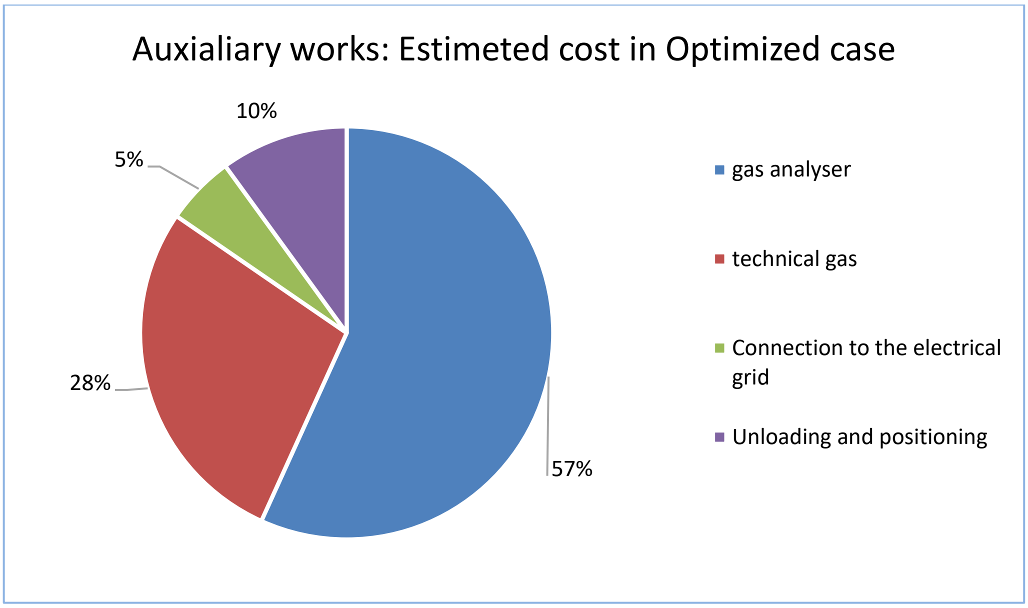


Figure 40-Relative weight of each item in the framework of estimated cost of the Auxiliary works

Despite the reduction of two items of them, the trend of the percentage reported in the figure is very similar to the actual case. Anyway, the final result is that the total cost is decreased.

5 Results

In the previous chapter, they are described each step aim to obtain the reduction of each item of each macro area. However, in order to understand the efficacy of the hypothesis made, in the first part of this chapter is shown the data reworking as seen to the actual cost. Then a comparison between these values with those previously obtained is performed. Finally, the total cost of the site preparation is evaluated.

In the following table the data reworking is shown:

		Excavation	**Work in reinforce concrete**	**Raw material cost (tubes, valves..)**	**Cost of labour**	**Total cost**	**Variation**
Ducts	grounded ducts	€ 0	€ 0	€ 76.219	€ 24.840	€ 112.493	-75%
	pipe racks	€ 52	€ 776	€ 2.646	?		
	Electrical ducts	€ 0	?	€ 7.960	?		
	Sum	€ 52	€ 776	€ 86.825	€ 24.840		
Platform	**Excavation**	**Work in reinforce concrete**	**platform to UPS**	**Platform to technical gas**		€ 14.817	-60%
	€ 2.345	€ 12.472	-	-			
Technical building	**Metal framing works**	**Technical building works**	**UPS building**	**Electric cabinet**		€ 111.427	-48%
	€ 4.305	-	-	€ 107.122			
Safety and auxiliary works	**Safety cost and auxiliary works**	**gas analyser**	**technical gases**	**Electrical grid connection**	**Unloading and position**	€ 67.899	-47%
	€ 13.302	€ 31.000	€ 15.178	€2958	€ 5.461		

Table 11-Reworking data of the works of Optimized plant

As actually cost table (collegamento), the cost of ducts represents the highest part, as well as the cost needed to realize the platform is the lowest one. However, the ducts cost that in previous case was approximately the half of total cost, now, thanks the control volume hypothesis and cable ducts one, it is approximately one third of the total cost. As can be seen, now its costs referred to excavation and works in reinforce concrete are negligible, while the other items are reduced a lot.

The hypothesis to take into account only the strictly necessary works and the well dimensioned components allowed halving the cost of the safety and auxiliary works cost.

On the other hand, the halving obtained on the technical building is due mainly to the hypothesis of utilize a container as technical building.

Finally, the reduction on the platform cost is duo to both the optimal shape chosen and the missing of grounded ducts, that has been caused a lower excavation and reinforce concrete thickness.

In conclusion, the following table shows the total cost of each macro area and the total plant cost:

	Actual Cost [€]	**Estimated Cost [€]**	**Reduction**
Mechanical Works	174.562	65.502	-63%
Electrical Works	173.913	100.819	-42%
Civil Works	191.920	23758	-88%
Clean-up system	221.087	132.652	-40%
Auxiliary works	91.677	54.597	-40%
TOTAL	853.159	377.328	-56%

Table 12-Comparison between actual cost and the estimated one of the main works

As can be seen, each macro area has a reduction between 40% and 88%, while the site preparation cost has a reduction of 56%. However, to include any unexpected items, the site preparation cost is increased approximatively of 6% in order to obtain the convenient value of **400.000€**.

6 Discussions and Conclusions

The actual DEMOSOFC scenario shows a technology, the fuel cell, that is not able to penetrate the market. In fact, it is very far from the ICE technology. By a numerical point of view, to perform a 174kWe plant size with ICE technology needs approximately 800.000€, while DEMOSOFC cost nearly 4.000.000€, as can be seen by the following table:

	Actual cost [€]
Site preparation cost	853.159
SOFC modules cost	3.037.989
DEMOSOFC cost	3.891.148

Table 13-Total DEMOSOFC cost

Both site preparation cost and SOFC modules cost are too higher to be able to compete with the standard technology. Then, to try to perform this aim, the study is divided in two theses, one to each aspect.

To perform the reduction of the site preparation cost, some hypotheses are made based on an analysis on the realized works and on its costs. They are following summarized:

- Control volume on DEMOSOFC area
- Only one 175kWe fuel cell module
- Use of cable ducts
- Container for technical building
- No lead&lag configuration

Thanks theme and considering a little overestimation to include unexpected items, the cost in the redesign case is approximatively 400.000€, that correspond to a reduction of 56% related to the starting point. It is shown next table:

	Actual Cost [€]	Estimated Cost [€]	Reduction
Mechanical Works	174.562	65.502	-63%
Electrical Works	173.913	100.819	-42%
Civil Works	191.920	23758	-88%
Clean-up system	221.087	132.652	-40%
Auxiliary works	91.677	54.597	-40%
TOTAL	853.159	377.328	-56%

Table 14-Comparison between actual cost and the estimated one of the main works

However, only this result is not sufficient to compare this technology with standard one. Then, the other thesis concerning SOFC module cost, that is performed by Marco Napoli, shows a cost of SOFC of, approximatively, 1.200.000€ in short term scenario and 700.000€ in long term scenario. They correspond respectively to a reduction of 60% and 77% related to current scenario.

Then, summarizing the two shares, it is possible to obtain a total plant cost of 1.600.000€ in short term scenario (STS) and of 1.100.000€ in long term one (LTS). They correspond respectively to a reduction of 59% and 72% related to the total plant cost in the current scenario. Moreover, they correspond to the ratios of 9200€/kW and 6350€/kW in the two scenarios. In the following figure, these results are shown and their relation with the standard technology too:

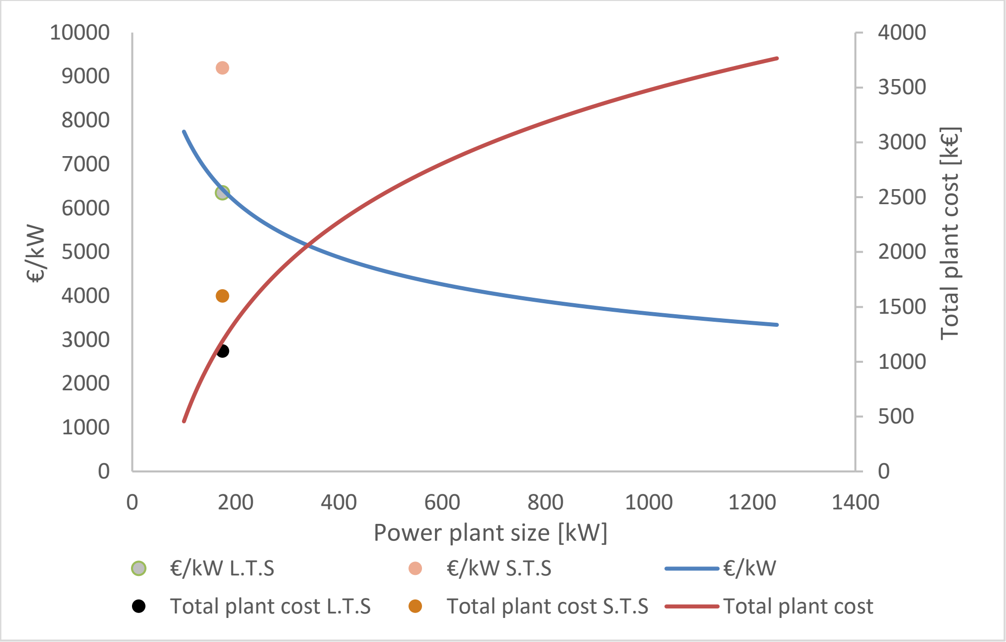


Figure 41- Comparison among the standard technology and the evolution of short term scenario and long term one to SOFC technology

As can be seen, in the long term scenario the SOFC technology have almost the same cost of the standard technology. Then, in this case, SOFC technology represent a good alternative to the traditional one. Instead, in the short one it is more expensive. However, also in this case can be evaluated its use, because the standard technology can only produces thermal energy while the SOFC one is a CHP. Considering that the WWTP is a very energetic expensive plant and that DEMOSOFC is able to produce around 30% of its electrical demand, this technology could be also interesting from an economic point if view. In fact, in the short term scenario, the installation cost is higher than standard technologies, but operational plant costs are lower and they might permit to have a good cashback time. Then, also in this scenario the development of this technology looks possible.

On the other hand, omitting the CHP property, an important aspect that was took into account to perform the DEMOSOFC project is about its eco-friendlier properties. Then, from this point of view, in order to respect the environment international agreements and to avoid the fine, the EU (or some country of them) can decide to invest in this technology through government incentives.

7 Reference

[1] *Enhancing the Energy Efficiency of Wastewater Treatment Plants through Co-digestion and Fuel Cell Systems* – M. Gandiglio, A. Lanzini, A. Soto, P. Leone, M. Santarelli

[2] http://www.demosofc.eu/?page_id=873

[3] https://www.sciencedirect.com/topics/earth-and-planetary-sciences/waste-water-treatment-plant

[4] Site *preparation for the installation of the DEMO* – A. Zanghì, M. Gandiglio, A. Lanzini, M. Santarelli, U. Fausone, B. Biddau

[5] *Detailed engineering of the DEMO* – A. Lanzini, M. Gandiglio, D. Papurello, M. Santarelli, F. Pognant, G. Vaudano, U. Fausone, T. Hakala, M. Liukkonen, H. Stenberg

[6] *SOFC-ESE-l02 Computo Metrico Estimativo* – Coop. Viridia S.C.

[7] *Computo metrico estimativo* – Icef Sviluppi Immobiliari S.R.L

[8] *Computo metrico estimativo* – Baratella F.lli Srl

[9] *Offerta Biokomp* – Bio-komp srl

[10] *Virida SAL 1* e *Viridia SAL 2* – Coop. Viridia S.C.

[11] *DL ICEF-Sal SAL 1*, *DL ICEF-Sal SAL 2*, *DL ICEF-Sal SAL 3* – Icef Sviluppi Immobiliari S.R.L

[12*] DL-BAR-Certificato di Pagamento 1 rata*, *DL-BAR-Certificato di Pagamento 2 rata*, *DL-BAR-Certificato di Pagamento 3 rata*– Baratella F.lli Srl

[13] *Fatture Biokomp* – Bio-komp srl

[14] *Costi di produzione di energia elettrica da fonti rinnovabili* – R. Marchesi, P. Bombarda, A. Casalegno, L. Colombo, M. Guilizzoni, A. Lucchini, A.G. Manfredi, F. Rinaldi, A. Rota

[15] *Advancing Europe's energy systems: Stationary fuel cells in distributed generation* – H. Ammermann, P. Hoff, M. Atanasiu, J. Aylor, M. Kaufmann, O. Tisler