DEMOSOFC

Project n° 671470

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

Deliverable number 5.6

Report on the LCA of the DEMO system

Due Date of Delivery	M62
Actual Submission Date	28/01/2021
Lead Beneficiary	Politecnico di Torino
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Work package	WP5
Dissemination Level	PU
Nature	R
Version	1.0
Total number of pages	44

Abstract:

This work assesses the environmental impacts of an industrial-scale Solid Oxide Fuel Cell (SOFC) plant fed by sewage biogas locally available from a WasteWater Treatment Plant (WWTP).

Three alternative scenarios for biogas exploitation have been investigated and real data from an existing integrated SOFC-WWTP have been retrieved: the first one (Scenario 1) is the current scenario, where biogas is exploited in a boiler for thermal-energy-only production, while the second one is related to the installation of an efficient SOFC-based cogeneration system (Scenario 2). A thermal energy conservation opportunity that foresees the use of a dynamic machine for sludge pre-thickening enhancement is also investigated as a third scenario (Scenario 3). The life cycle impact assessment (LCIA) has shown that producing a substantial share of electrical energy (around 25%) via biogas-fed SOFC cogeneration modules can reduce the environmental burden associated to WWTP operations in five out of the seven impact categories that have been analyzed in this work. A further reduction of impacts, particularly concerning global warming potential and primary energy demand, is possible by the decrease of the thermal request of the digester, thus making the system independent from natural gas. In both Scenarios 2 and 3, primary energy and CO2 emissions embodied in the manufacture and maintenance of the cogeneration system are neutralized by operational savings in less than one year.

Keyword list: life cycle assessment; biogas; fuel cell; solid oxide fuel cell; wastewater

Summary

Nomenclature

ADP	Abiotic Depletion Potential of elements
AP	Acidification Potential
APU	Auxiliary Power Unit
CHP	Combined Heat and Power
EP	Eutrophication Potential
FC	Fuel Cell
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCT	Life Cycle Thinking
ODP	Ozone Depletion Potential
PED	Primary Energy Demand
POCP	Photochemical Ozone Creation Potential
SOFC	Solid Oxide Fuel Cell
WWTP	Waste Water Treatment Plant

1. Introduction

Fuel Cells (FCs) are expected to play an important role in reducing environmental burdens associated to energy conversion technologies in order to achieve the EU objectives [1]. Fuel cells are particularly interesting due to their high efficiency, modularity, excellent partial load performance, low pollution emissions and possible integration with other systems (e.g. steam or gas turbines) [2], [3]. Solid Oxide Fuel Cells (SOFCs) are suitable for distributed stationary power generation because of their fuel adaptability (a variety of hydrocarbon fuels can be employed) and the possibility of cogeneration since operating at high temperature (around 800°C).

For sustainability evaluations, various policy documents underline the need of accurate information related to the environmental performances of products and service, especially in case of the introduction of innovative technologies on the market [4]–[6]. To assess the environmental sustainability of a product/service/new technology, a life cycle approach should be adopted in order to lead policy makers and consumer decisions and to introduce sustainable innovative technologies on the market [4]–[6]. Among the tools available to assess the environmental impacts of new technologies, Life Cycle Analysis (LCA) is a standardized methodology [7]–[9] widely used by the scientific community.

Large size fuel cell systems have shown a growing interested in the scientific world and in the market sector, but LCA of similar systems is not always taken into account. Few works can be found on LCA of real fuel cell plants.

Jing et al. [10] have developed a multi-optimized SOFC model evaluating, for a specific case study, environmental and economic benefits. Anyway, when authors are talking about environmental analysis, they are mostly referring to emissions analysis. Life cycle analysis is indeed a comprehensive study able to evaluate the impact of a specified system over its entire lifetime. A recent study from Benveniste et al. [11] deals with the LCA of micro-tubular SOFC for Auxiliary Power Units (APU) fed by liquefied propane gas: results show a reduction of 45% in terms of CO_2 equivalent emissions and of 88% in terms of Primary Energy consumption compared to conventional Diesel APU systems. Furthermore, Global Warming Potential (GWP) and primary energy impacts could be cut down only applying a global reduction of the energy consumed in the manufacturing and an improving in the system efficiency.

The European Project FC-Hy Guide [12], [13] has extensively used life cycle assessment to better understand engineered solutions towards more environmentally sound fuel cell production and use. A guidance manual for LCA application to FC technologies, processes and systems has been developed and includes essential information on how to develop LCA of hydrogen-based and fuel cell technology, with details on the processes to be included, the approach, the steps and inputs/ outputs of the system [14]. Anyway, FC-Hy Guide does not include a real case study application of the proposed method with SOFC, which is indeed developed in the presented work. The project has analyzed, in a published work [12], the LCA of a Molten Carbonate Fuel Cell (MCFC). Key results from the MCFC analysis have been that the impact of MCFCs on abiotic depletion and on global warming impact categories should be reduced by optimizing the electricity use in the production process or replacing such electricity with electricity from renewable sources [12]. Furthermore, results show that chromium steel used in the reformer, power conditioner and non-repetitive parts of the stacks should be decreased due to its impacts on human toxicity; recycling. Finally, as expected, natural gas feedings affects heavily on global warming.

Despite some critical aspects, other works on the LCA analysis of Molten Carbonate Fuel Cells show benefits compared to traditional technologies like micro turbines [15]–[17]. Staffell et al. also analyzed energy consumption, process related emissions and carbon payback time of Combined Heat and Power (CHP) systems based on Alkaline Fuel Cells or Solid Oxide Fuel Cells [18]. Comparison between fuel cells (MCFC) and other technologies (Internal Combustion Engines and Gas Turbines) was performed in 2010 by Bargigli et al. [19]: results pointed out the hybrid MCFC-GT system as the best option in terms of both efficiency and environmental impact, followed by the ICE.
Other works are available in literature related to Polymer Electrolyte Fuel Cells (PEMFCs) because of their interest in the automotive sector. Evangelisti et al. [20] have compared a FC vehicle with a standard ICE-base vehicle and an electric vehicle. The production process showed a higher environmental impact for the FC vehicle compared to the production of the other two vehicles power sources (and this is due to the hydrogen tank and the fuel cell stack). Anyway, a potential reduction of 25% in the climate change impact category has been also detected. Over the entire life, ICE-based vehicles show indeed the worst performance because of fossil fuel use. One option to reduce environmental impact in terms of, for example, ADP of FC-based vehicles is the option of platinum recycling at end of life, as analyzed by Duclos et al. [21]. Their work shows that more than half of the main impacts of the membrane-electrode-assembly can be avoided for four relevant impact categories if platinum is recovered in the end-of-life of the product.
A similar state-of-the-art knowledge on LCA is also available – even if with a smaller number of contributions – for SOFCs: different works are available and are associated to the different fields of applications of SOFC technology: APU, micro-CHP, large-size CHP, etc. Longo et al. [22] have analyzed LCA of PEMFC and SOFC in the ‘Hydrogen Economy’ book, edited by Academic Press; here the authors provide a literature review of available LCA researches to point out the environmental impacts of the FCs. Mehmeti et al. [23] published a recent (2016) work reviewing the state of the art of LCA in SOFC systems. This is one of the most interesting and comprehensive works on the state of the art of SOFC systems.
Moving more specifically to SOFC application in cogeneration mode in industrial plants, few works are also available in literature. Tonini et al. [24] analyzed biomass-based energy system in Denmark by means of LCA tool. The authors analyzed future scenarios (2030 and 2050) by introducing innovative energy system for transport fuels supply. SOFCs, fed by biogas and syngas were used for

electricity production in the future scenarios. Thanks to the combination of the different technologies involved, a reduction ranging from 66 to 80% in GHGs emissions was found.

Sadhukhan at al. [25] performed a comparison between biogas-fed SOFC, PEMFC, micro-GT and ICE in terms of environmental performance: in terms of avoided GWP, Acidification Potential (AP) and Photochemical Ozone Creation Potential (POCP), biogas based PEMFC micro system is depicted as the most beneficial compared to the equivalent natural gas based systems. End-of-life management of SOFC materials [26] is also another un-explored area, which could lead to interesting scenarios.

Most of the works related to LCA of SOFC systems [27], [28] are referring to the same database for SOFC production inventory. One of the main criticality of data collection on SOFC production is that there are not many companies, worldwide, which are producing SOFC system at industrial scale. The key novelty of the presented work is related to the use of recent and updated sources for data collection, both in terms of SOFC production and operation. In particular, the data of the operation phase are taken from a real project managed by the Authors, named DEMOSOFC (described below), and the use of real data represents a unique and significant added value for the LCA study.

For what concerning SOFC production, a 2015 report from Ernest Orlando Lawrence Berkeley National Laboratory is available [29]. Thanks to the cooperation with the worldwide largest companies for SOFC production, the report analysed SOFC applications for use in CHP and power-only from 1 to 250 kW-electric. The resulting total cost of ownership includes the direct manufacturing cost modeling framework, operational costs and life-cycle impact assessment of possible ancillary financial benefits during operation and at end-of-life.

For what concerns the operation phase inside and the SOFC management in a real industrial environmental, data have been retrieved from the DEMOSOFC project [30]–[32]. The project is related to the installation of the first industrial size biogas-fed SOFC plant in Europe. The three SOFC modules, supplied by Convion [33], produce 174 kWe and around 90 kW-thermal; all the energy is self-consumed within the Waste Water Treatment Plant (WWTP) of Collegno (Torino, IT), where biogas is produced from sewage sludge. The first SOFC module is running since October 30th, 2017. This work thus assesses the potential environmental impacts of a CHP plant that employs medium size SOFCs, fed by biogas produced by a WWTP facility, with a life cycle (cradle to gate) approach. The first section is related to the methodology presentation, the scenarios definition and the Life Cycle Inventory (LCI) (Section 3, 4 and 5), where all the input data are discussed. Then, results are shown and discussed in Section 6.

The main goal of this study is the characterization of the energetic and environmental burdens of the three WWTP case studies through sustainability and life cycle impact indicators. The LCA developed in this work is comparative, so benefits or disadvantages are relative to the so-called "*reference*" scenario.

2. Plant layout and scenarios definition

A WWTP could be simply divided in two sections (Figure 1): (1) a water line, in which wastewater undergoes to physical, biological and chemical treatments in order to meet the thresholds imposed by the existing standards; (2) a sludge line, where the organic matter separated during water purification is pumped towards the anaerobic digester. During the anaerobic digestion, microorganisms break down the organic substance contained in the sewage sludge and partially convert it into biogas. A WWTP needs electrical and thermal energy to sustain all these processes [34], [35].

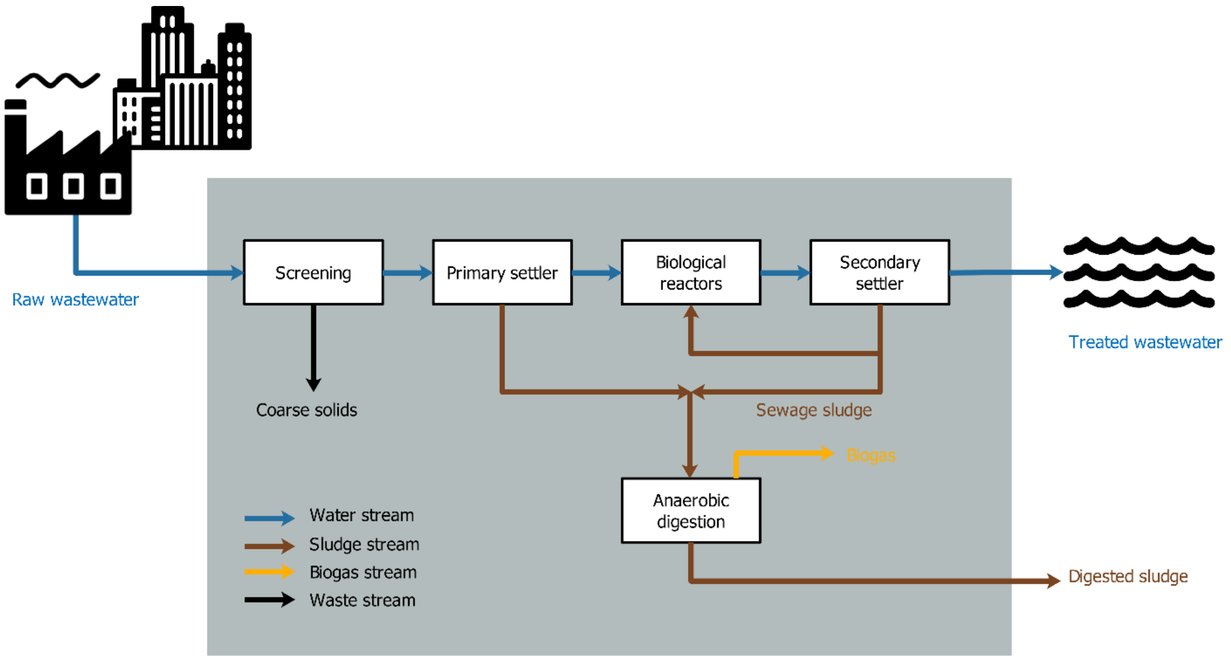

Figure 1. Simplified functional scheme of a WWTP.

Three alternative scenarios will be analysed for the WWTP:

- Scenario 1: the "*reference*" scenario in which all the electricity needed for operations is purchased from the grid and biogas is exploited in a boiler for thermal recovery or flared. No CHP system is installed and this represents the ante-DEMOSOFC scenario.

- Scenario 2: it foresees the installation of the SOFCs CHP system and biogas management improvements (since biogas is primarily sent to the CHP system and surplus gas, when available, is still used for thermal production in the existing boilers).
- Scenario 3: is similar to the second one but with an improvement in the anaerobic digestion line. The thermal demand of the anaerobic digester is indeed reduced by means of a dynamic sludge pre-thickening machine [36]–[40].

The WWTP analysed in this work is sited in Collegno, metropolitan city of Turin [41]. A brief description of what happens inside the plant is useful to understand its energetic and material needs. The focus is on sludge and biogas lines, since they are modified when the SOFC-CHP system is installed in the plant.

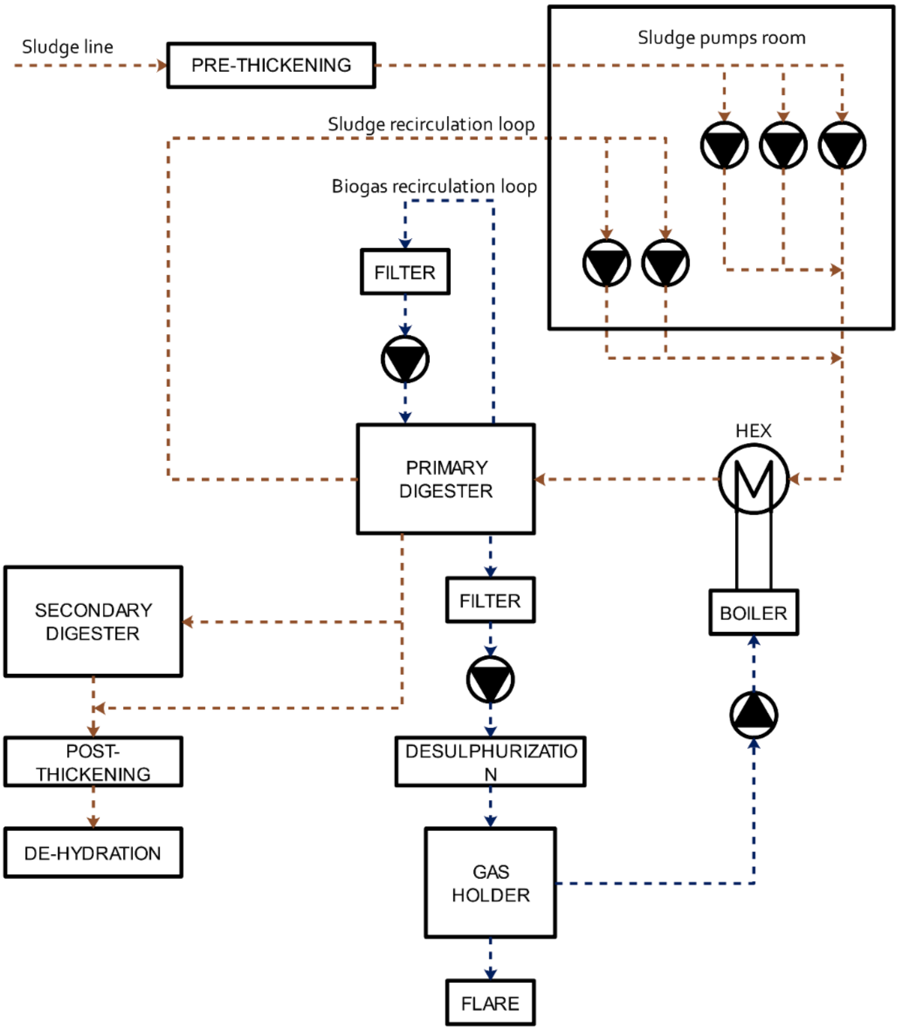

Figure 2. Scenario 1 (Reference scenario): biogas and sludge lines in the WWTP.

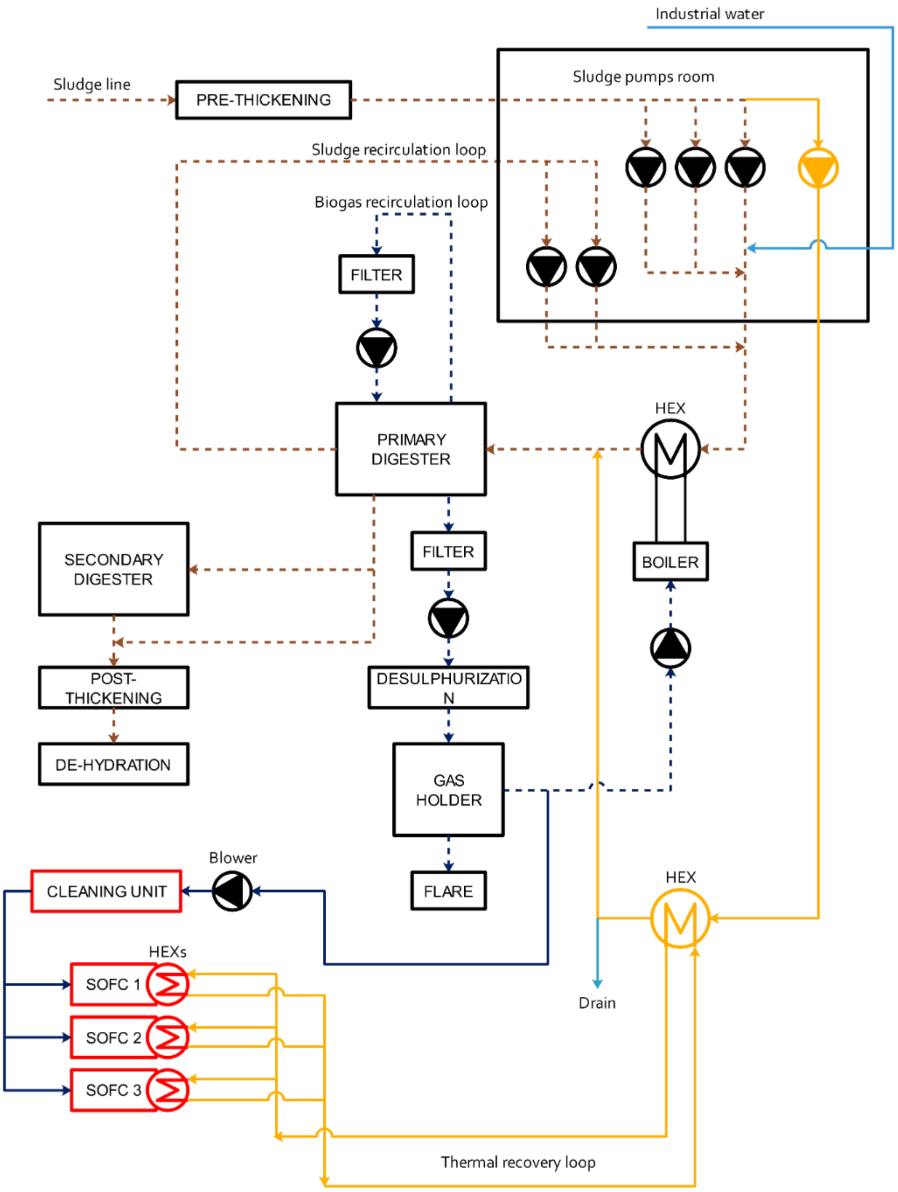

Figure 3. Biogas and sludge lines in the scenarios (2 and 3) with SOFC based CHP system.

In the Scenario 1 (Reference) (Figure 2), raw and activated sludge produced during wastewater treatment are pre-thickened in separated tanks exploiting gravitational forces. Secondary sludge is treated with ozone to reduce the total amount of sludge volume to be treated. Although ozonisation is not the best option for what concerns anaerobic digestion yield– biogas produced per capita is lower respect to other plants - it is an optimal process from the point of view of the overall plant since it reduces the total amount of sub-products. Raw and activated sludge are both heated before entering the digester, which is maintained in a mesophilic range of temperatures (35-45°C). Part of the sludge and of the produced biogas is continuously re-circulated in the tank to maintain high renewable-gas yield. The digested sludge is sent to a post-thickener, a press filter, to reduce the water content and make it available as fertilizer. Because of variable wastewater intakes, sludge and biogas productions fluctuate, so it is important the presence of a gas holder. The only use of biogas in this research is in boilers for producing the thermal energy needed for self-sustaining the anaerobic digestion process. Thermal demand of the anaerobic digester is determined by the sum of energy needed for sludge heating up to set point temperature (around 42°C) and that required to compensate losses through walls and pipes. Biogas in excess is flared. When biogas flow is not sufficient, the thermal demand is satisfied by natural gas taken from the network and feeding the boilers. The whole amount of electricity is purchased from the grid. Annual electrical and natural gas consumptions and average biogas yield and production rate are provided by the owners of the plant (SMAT, [41]).

In the Scenario 2, WWTP energetic self-sufficiency is improved through the installation of a not-conventional CHP unit. The choice of SOFC technology is motivated by its very high electrical efficiency, and the operation in CHP mode. Its adoption in the project is oriented towards its market introduction on industrial scale by means of a demonstration of its energetic and environmental performance [30]. SOFCs generate electricity directly from the chemical energy contained in the biogas, with high efficiency and near-zero emissions of pollutants (e.g. CO, NO_x and hydrocarbons). The disadvantages are fuel cell sensitivity to biogas contaminants (in sewage biogas mainly sulphur and silicon compounds) and to thermal cycles (shutdown should be avoided). As shown in Figure 3, the change in infrastructure in the WWTP can be represented by three main sections:

- Biogas processing unit, where biogas is dehumidified, cleaned from harmful contaminants and compressed;
- SOFCs cogeneration modules (total power 174 kWe), where electrical energy is produced and used for plant internal needs;
- Heat recovery section, where thermal power contained in exhaust gas exiting from SOFCs is recovered and transferred to the sludge entering the digester;

Biogas handling is changed, since now its primary goal is feeding the CHP modules while the surplus is sent to boilers to satisfy digester thermal demand. Moreover, as in the reference case, biogas in excess in the gas holder is burned by the flare system. When the amount of biogas in the gas holder is not sufficient to cover digester thermal demand, natural gas is withdrawn from the grid. In this second scenario, the electrical consumption of the WWTP is higher, owed to absorption of power of some components in the balance of plant (e.g. biogas compressor, chillers and control system).

The Scenario 3, in which the SOFC CHP unit is still present, foresees a reduction of the thermal demand for the anaerobic digestion process through an increase of the level of thickening of sludge (dry matter from 2.7% to 6.4% in weight) [42]. The reduction of the thermal load is a consequence of the lower water content inside the digester, and makes the system independent from the integration with natural gas. At the same time, the installation of a dynamic thickening machine is responsible of a slight increase in electrical consumptions of the WWTP.

	1st scenario	**2nd scenario**	**3rd scenario**
Electrical energy	Grid 100%	SOFC modules 25.2% Grid 74.8%	SOFC modules 25.1% Grid 74.9%
Thermal energy	Biogas burned 93% NG burned 7%	SOFC modules 23.5% Biogas burned 31.4% NG burned 45.1%	SOFC modules 43% Biogas burned 57% NG burned 0%
Biogas handling (*)	Boilers 82.6 % Flare 16.6 %	SOFC modules 71.6% Boilers 27.4% Flares 0.2%	SOFC modules 71.6% Boilers 27.4% Flare 0.2%

(*) Biogas losses from anaerobic digester are equal to 0.8 % in all the scenarios.

Table 1. Biogas management and energy sources in the three scenarios.

Table 1 shows the resulting share of electrical and thermal energy coverage and the biogas handling with the plant. Input data for the development of the energy balance are:

- SOFC electrical efficiency: 53.1% [33]
- SOFC thermal efficiency: 25.8% [33]
- Yearly equivalent capacity factor: 95% (assumption)
- Ordinary maintenance per year: 7.5 days (assumption)
- Digester thermal load (daily-based) definition as described in [43]
- Electrical load (monthly-based) from SMAT data. Average yearly consumption equal to 20.88 kWh/PE/y, in line with the work developed by Panepinto et al. on a similar SMAT-owned WWTP [37]
- Boiler efficiency: 90%
- Biogas average macro-composition: 60% CH_4 - 40% CO_2

As can be seen from Table 1, in scenario 1 all electricity is purchased from the grid and heat is supplied mainly by biogas (with a NG contribution only in winter season). In scenario 2, around 25% of the electrical energy is self-produced thanks to the installation of the SOFC system. Thermal energy provided by NG is increased (from 7 to 45%), because of the use of biogas in the CHP unit. This criticality is solved in the third scenario where electricity share is equal to the second one, but thermal load is reduced (thanks to the installation of a sludge pre-thickening system) and consequently NG consumption is zero.

3. Methodology

3.1 General principles

Life Cycle Thinking (LCT) is the basic concept referred to the need of assessing environmental and resource use burdens of a system adopting a holistic perspective, from raw material extraction to end of life, also in order to minimize the risk of environmental impact shifting [44].

Life Cycle Assessment (LCA) [7]–[9] can assist in identifying opportunities to improve environmental performance of a system and informing decision makers by means of relevant impact indicators. In particular, the Life Cycle Impact Assessment (LCIA) phase includes the collection of indicator results for the different impact categories, which together represent the LCIA profile of the analysed system. If the final user of LCA results would like to further simplify category indicators, optional steps as normalization, grouping and weighting could be performed [45].

3.2 System boundaries

The life cycle phases included in this work are manufacturing and maintenance of the SOFCs CHP system and operation of the WWTP in the three selected scenarios. End of life of products belonging to the analysed system is not included since no exhaustive and satisfying information are available yet. The possibility of recycling and reusing some precious materials inside the studied system is clear and evident, so this can be cited as the first limitation of the here performed LCA, and further investigations are recommended.

The examined WWTP scenarios differ mainly in their infrastructures and in the way of handling biogas produced by the anaerobic digestion process (Figure 2 and Figure 3). Therefore, the level of energy dependence from external resources (electricity and natural gas) used for sustaining wastewater processes changes among the analysed scenarios (Table 1).

The comparative nature of this LCA is reflected in the definition of system boundaries of the three scenarios. All the processes shared among the compared scenarios are left outside of the boundaries. In Figure 4 and Figure 5 the processes, material and energy flows used to characterize the three scenarios are represented. The main foreground processes are boilers, digester, WWTP operations and SOFCs CHP system manufacture, operation and maintenance.

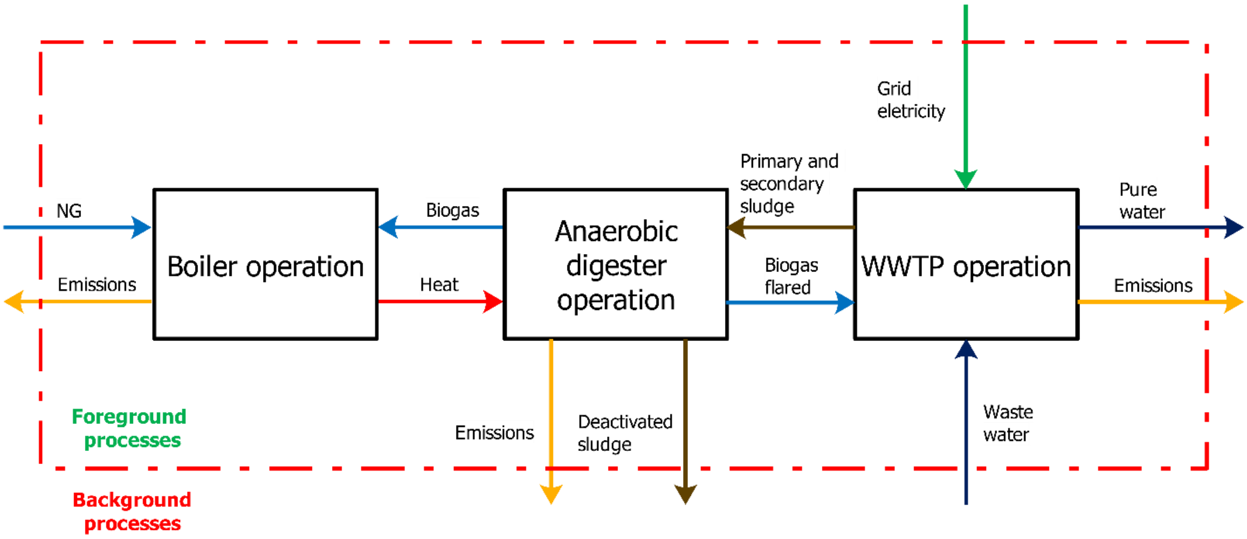

Figure 4. Boundaries of the reference WWTP (scenario 1).

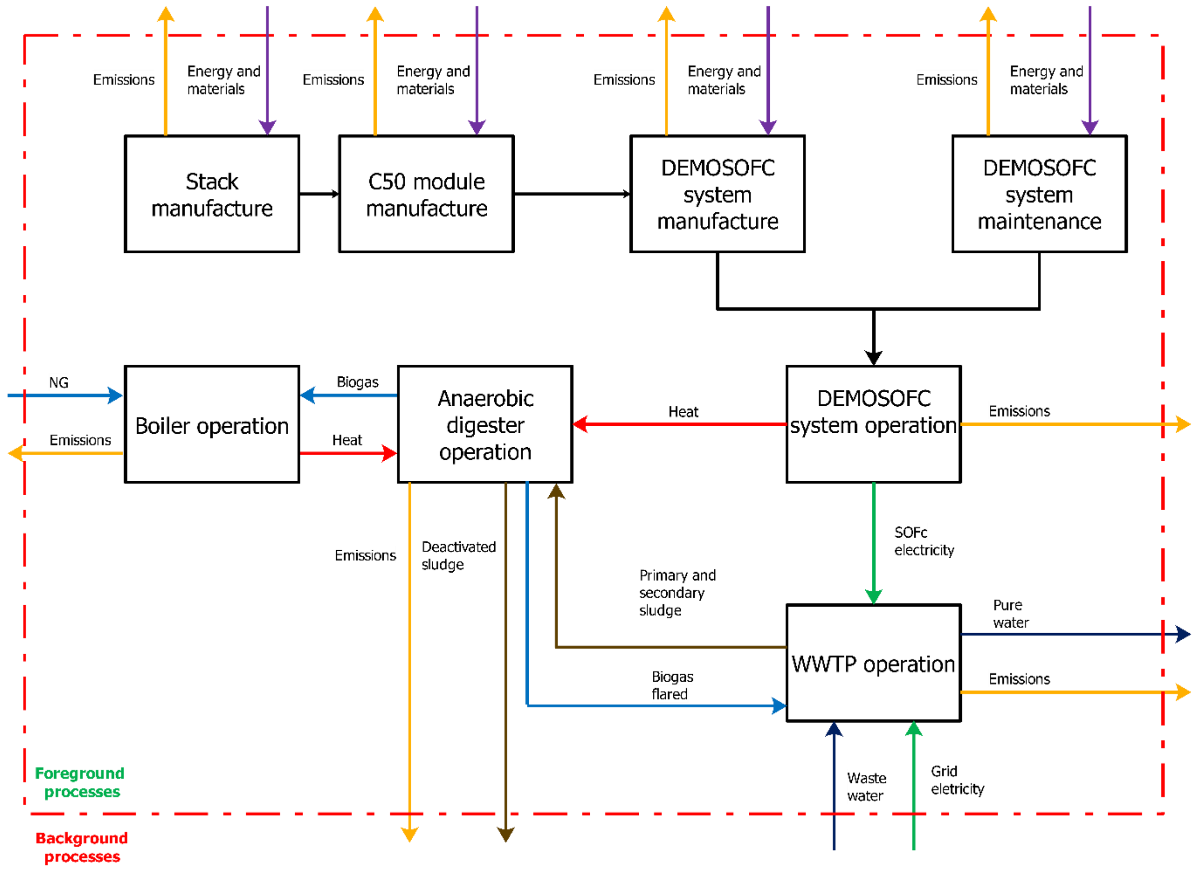

Figure 5. Boundaries of the WWTP with a SOFC based cogeneration system (scenario 2 and 3).

3.3 Functional unit

In a LCA, the functional unit allows the comparison of systems, which are functionally equivalent; in this study, it is the wastewater treated by the plant in one year (around 14 Mm^3/yr for the SMAT Collegno WWTP [41]). The purification process requires high quantities of electricity, especially for the secondary biological treatment, and to guarantee sludge and water circulation within the plant [46]. Instead, thermal energy is needed to sustain the anaerobic digestion process that is optimized only in specific range of temperature. What can be established by fixing this functional unit and through a comparative LCA is if the SOFC based CHP system installed in the WWTP is sustainable from the environmental and energetic point of views.

3.4 Impact assessment method and indicators

Accordingly to the guidance document for performing LCA on fuel cell and hydrogen technologies [14], CML midpoint characterization factors (2010 version) has been selected. This method is in line with European environmental policy goals, widely used in practice, sufficiently robust and consistent with previous analyses performed by the authors [47].

In order to reduce as much as possible the subjectivity associated to this work, midpoint impact categories has been chosen. Results expressed as damage to area of protection (e.g. human health, biotic/abiotic environment and resources) are simpler to understand but are more sensitive to specific hypothesis adopted in each characterization model. For the same reason, non-normalized and non-weighted results are preferred.

The impact categories and the corresponding indicator employed are:

- Global Warming Potential (GWP) in kgCO_2-eq
- Acidification Potential (AP) in kg SO_2-eq
- Abiotic Depletion Potential of elements (ADP) in kg Sb-eq
- Eutrophication Potential (EP) in kg PO_4-eq
- Ozone Depletion Potential (ODP) in kg CFC11-eq,
- Photochemical Ozone Creation Potential (POCP) in kg C_2H_2-eq
- Primary Energy Demand from renewable and non-renewable resources (PED) in MWh-eq.

In order to further clarify the results, energy and carbon payback times are finally calculated. Energy payback time is determined as the ratio between the embodied energy through the system entire lifetime and the gross energy savings; carbon payback time is the ratio between the same embodied emissions and the gross CO_2 savings. The aim is showing in how many years of operation of the WWTP with SOFCs CHP system installed, the savings in primary energy and CO_2 emissions, compared to the reference scenario, can balance the energy requirements and the carbon dioxide generated during manufacture and maintenance.

For the implementation of the model, the LCA software GaBi® and the Ecoinvent 3.1 Database are used

4. Inventory

For each scenario previously introduced, the unit processes included in the boundaries are analysed and the compilation of all relevant input/output flows, in reference to the functional unit, is performed. Looking at Figure 4 and Figure 5 it can be seen that in Scenario 1 (reference), where biogas is exploited only in the boilers for thermal power production, operative phases associated to the WWTP itself are part of the inventory. On the contrary, in scenarios 2 and 3, in which a cogeneration system is installed besides existing boilers, manufacture and maintenance of the SOFC-based CHP system are also included.

4.1 SOFC stack manufacturing

A solid oxide fuel cell is a device allowing the direct conversion of chemical into electrical energy, at high temperature. A single cell consists of three layers, a dense electrolyte between two porous electrodes (anode and cathode). The power provided by a single cell is very low and, to overcome this limitation, they are connected in series to form a stack by means of interconnector plates, manifolds, flow fields and sealant. This unit process is analyzed in detail since it is the core of the CHP system and innovative materials are continuously tested and employed to improve the overall efficiency.

Information about fuel cells manufacture are taken from a work developed at Lawrence Berkeley National Laboratory [29]. The design and manufacturing steps of the SOFCs closely follow those of Fuel Cell Energy Inc., which has acquired Versa Power System. Geometrical and functional characteristics and number of cells interconnected per each stack are reported in

Fuel Cell Energy (Versa Power) SOFC		
Total plate area	540	cm^2
EEA dimensions	18.15 x 18.15	cm

Actively catalized area	329	cm^2
Single cell active area	299	cm^2
Gross cell inactive area	45	%
Current density	0.35	A/cm^2
Reference voltage	0.8	V
Power density	0.28	W/cm^2
Cell power	84	W
Cells per stack	130	units
Gross stack power	11	kW
Net stack power	10	kW

Table 2.

Fuel Cell Energy (Versa Power) SOFC		
Total plate area	540	cm^2
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Table 2. Characteristics of SOFCs manufactured by Versa Power [29], [48].

It is important, whenever a manufacturing process is analysed, to fix the production volume in order to normalize material and energy flows respect to a reference unit, in this case a single stack. From [29] it has been chosen a production volume of 50’000 stacks per year equal to 32’500’000 electrode-electrolyte assembly (EEA) cells per year. Another important aspect associated to a manufacture analysis is the determination of line process parameters (e.g. line availability, performance and yield). These are linked to the level of automation and to the annual production volume of the site.

The part of the cells in which electrochemical reactions occur is the electrode-electrolyte assembly (EEA) which is planar and anode supported. The anode is tape casted while the other layers are deposited on the support by screen printing machines (see Table 3 for details).

Component	Materials	Thickness [μm]	Process
Anode	Ni/YSZ	700	Tape casting
Anode-electrolyte interlayer	50%NiO+50%YSZ	10	Screen printing
Electrolyte	YSZ	10	Screen printing
Cathode-electrolyte interlayer	50%LSM+50%YSZ	10	Screen printing
Cathode	LSM	50	Screen printing

Table 3. Characteristics and manufacturing processes of EEA [29], [48].

With a single step co-firing all layers are sintered together in a kiln. The set of processes included in the EEA manufacturing analysis are: slurry preparation, ball milling, de-airing and pumping, tape casting, screen printing, first quality control, co-firing, laser cutting and final quality control.

SOFC interconnectors are made of chrome based alloys (stainless steel 441) to maintain good physical property at elevated operating temperatures. To avoid chromium poisoning of the cathode, a manganese cobalt spinel oxide is physically vapor deposited and used as protective layer to prevent this problem. The processes involved in the interconnector manufacturing are stamping, cleaning and drying, PVD of the coating and final inspection. SOFC frames are made of the same materials of interconnectors and their manufacture foresees the use of analogous machines.

Seal is needed to prevent mixing and leaking of fuel and oxidant within/from the stack, to provide electrical isolation of cells and mechanical bonding of components. Glass seals are usually employed in joining planar SOFC. Cell to frame seal is applied for the cell to frame joining while cell to cell seal is applied during stack assembly. Steps involved in the sealing process are ball milling of the glass paste and heating under a static load in a furnace.

A semi-automatic stack assembly line is considered where repeat units are stacked up and current collectors or end plates are attached to both ends of each stack. A final fully automated conditioning and testing station is used for monitoring physical, chemical and electro-chemical properties and performance.

In Table 4 the input data are reported, where the reference unit is the manufacture of one stack of 10 kW nominal net power.

Material/energy flows	Value	Unit

Electrode-electrolyte assembly		
NiO	12.3	kg
8YSZ	4.47	kg
LSM	1.07	kg
Dibutyl phthalate (plasticizer)	1.46	kg
Polyvinyl Butyral (binder)	1.46	kg
Methocel A4M (binder)	0.97	kg
n-Butyl acetate 99,5% (solvent)	4.39	kg
2-Butoxyethanol (solvent)	0.55	kg
Carbon black (pore former)	0.95	kg
Electricity consumption	295	kWh
Interconnect and frame manufacture		
441 SS	43.54	kg
MCO	0.73	kg
Electricity consumption	433	kWh
Glass seal production & repeat unit assembly		
Glass powder	0.182	kg
N-butyl acetate (solvent)	0.050	kg
Polyvinyl butyral (binder)	0.018	kg
Benzyl n-butyl pht. (plasticizer)	0.014	kg
Electricity consumption	234	kWh
Stack assembly and testing		
441 SS	29.68	kg
Electricity consumption	121	kWh
Emission to air	**Value**	**Unit**
Electrode-electrolyte assembly		
Carbon dioxide	4.32	kg
n-Butylacetate 99,5% (solvent)	4.44	kg
2-Butoxyethanol (solvent)	0.55	kg

Table 4. Stack manufacture. Reference flow: 1 SOFC stack, net power 10 kW_{el} (data from [29], [48]).

Among the EEA manufacturing processes the most energy intensive is co-firing to which is associated around 73% of electrical demand. The total electrical consumption is 1083 kWh per stack manufactured (so around 108 kWh/kW) and a graph of contributions of processes is shown in Figure 6. Air emissions are related to the preparation of the slurry and to the complete evaporation of solvents in the drying step. Carbon dioxide emissions are taken and scaled from [47].

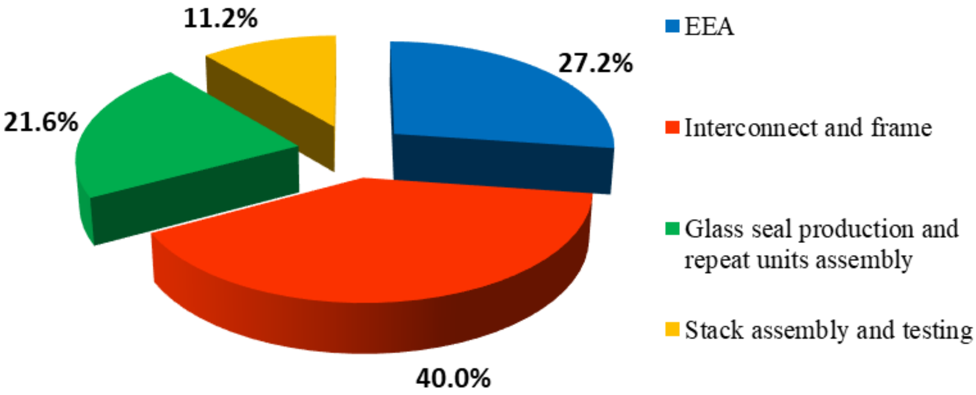


Figure 6. Energy consumptions associated to the stack manufacturing process.

In order to check the reliability of acquired data, a comparison with a merged inventory taken from literature [18] is performed. This study is quite old and analyses a different type of fuel cells (electrolyte-supported EEA). Nevertheless, there is a reasonable agreement between Versa Power and literature data.

4.2 CHP system manufacturing

The DEMOSOFC plant is composed of three C50 modules. C50 is a SOFC power generator with a nominal power output of 58 kW (AC net) produced by the Finnish company Convion [33]. Thanks to its modular architecture, multiple units can be installed in parallel to achieve higher power outputs. The components inside a module are stacks (in a quantity useful to reach the requested electrical power), pre-reformer, afterburner, fuel and air heat exchangers, blowers, filters, start-up components (e.g. electrical resistances), control system, piping and casing. Since no specific information on materials and energy needed for manufacturing a C50 module are available from Convion, literature has been revised to find data on some of these components [29], [47]. A general description of the balance of plant is useful to understand the compilation of inventory provided in

Material/energy flows	Value	Unit
SOFC stack, 10 kW_{el}	18	pieces
Steam reforming catalyst	53	kg
WGS catalyst	53	kg
Stainless steel	16’000	kg
Sheet rolling, stainless steel	16’000	kg

Reinforced steel	16’800	kg
Sheet rolling, steel	16’800	kg
Activated carbon, siloxanes + VOCs	1’300	kg
Activated carbon, H_2S	650	kg
Inverter (2.5 kW)	70	pieces
Natural gas, burned in industrial furnace	23.6	MWh_{th}
Electricity, IT consumption mix	8.35	MWh_{el}

Table 5.

Material/energy flows	**Value**	**Unit**
SOFC stack, 10 kW_{el}	18	pieces
Steam reforming catalyst	53	kg
WGS catalyst	53	kg
Stainless steel	16’000	kg
Sheet rolling, stainless steel	16’000	kg
Reinforced steel	16’800	kg
Sheet rolling, steel	16’800	kg
Activated carbon, siloxanes + VOCs	1’300	kg
Activated carbon, H_2S	650	kg
Inverter (2.5 kW)	70	pieces
Natural gas, burned in industrial furnace	23.6	MWh_{th}
Electricity, IT consumption mix	8.35	MWh_{el}

Table 5. Manufacture of the SOFC based CHP system. Reference flow: 1 SOFC CHP system, net power 174 kWel.

Biogas exiting the gas holder to feed the CHP units flows firstly through a recovery station, composed by a blower and a chiller, in order to have enough pressure to reach the treatment zone (positioned in another part of the WWTP) and avoid water condensation. In the biogas treatment section, filtration, compression, dehumidification and post-filtration are performed to satisfy the strict purity requirements imposed by SOFCs (max. 30 ppb sulphur, max. 10 ppb siloxanes). With the aim of improving the reliability and continuity of operation of the cleaning system, a lead and lag configuration is employed [30]. The clean-up reactors are adsorption vessels containing types of activated carbons specific for siloxanes and sulphur removal. Separated and dedicated feeding lines transport the purified biogas to the three SOFC modules.

Thermal recovery from C50 modules is performed by means of two interconnected loops. The use of a secondary water-glycol loop is essential to avoid fouling of heat exchangers inside the CHP units due to the dirty stream of sludge involved. Therefore, heat released by hot exhaust is transferred to the water-glycol mixture and then to the sludge directed towards the anaerobic digester. As previously said, based on the amount of thermal energy available from CHP units, a certain amount of sludge can be pre-heated by the SOFC, while the remaining part is heated up through the conventional hot water loops of boilers, which are fed by extra-biogas available in the gas holder or by natural gas from the network.

The three C50 modules are connected to the grid. During start-up, the fuel cells absorb power from the grid, while during normal operation power is exported. Connection of the SOFC modules with the external grid foresees medium voltage switchgear that is connected by means of transformers to the low voltage one. DC produced by SOFC must be converted through inverters in AC.

As it is easily understood, the analyzed balance of plant includes many components and it is not possible to perform a detailed data collection for each of them. Rough but at the same time necessary approximations are performed when compiling the inventory. The path chosen is to scale, update and modify datasets of similar systems available in other studies [47], [49] according to the size of the analyzed plant.

Since C50 unit has a rated electrical power of 174 kW and in the WWTP three modules are installed, a total amount of 18 stacks (10 kW each, according to the initial assumptions) is considered when compiling the inventory. Inside the modules, a material flow that cannot be neglected during data collection is associated to the catalysts present in steam reforming (SR) and water gas shift (WGS) reactors. In these components, methane contained in biogas is reformed to syngas before feeding the anode of SOFCs. The SR reaction is strongly endothermic and creates more gas volume as the hydrocarbon is converted. This means that high temperatures and low pressures favor it. Instead, WGS reaction is slightly exothermic so it is favored by low temperatures. Both reactions are catalyzed to improve methane conversion and decrease risk of carbon formation. The choice of the catalyst is influenced by several parameters: primarily activity and cost but also potential for carbon formation, heat transfer, strength and packing properties, pressure drop during operation [50]. Modern catalysts are for the most part made of supports onto which the active metal is impregnated. In this study, it has been supposed that the reactors use catalysts composed by 63% of alumina, 20% of nickel and the rest of silicon for steam reforming and iron for water gas shift. Information about amount of catalysts employed are taken from [51], [52], by scaling literature available data based on biogas flow to CHP modules. The same amount of catalyst in SR and WGS reactors has been assumed.

All the other components of a C50 module are assumed made of stainless steel since they operate at high temperatures. A single module weighs six tons and the amount of stainless steel has been determined by subtracting the mass of stacks and catalysts.

Concerning the fuel processing unit, the clean-up filtering media have been modelled. Focus is on activated carbons employed as adsorbent materials for sulphur, siloxanes and VOC removal. Activated carbons can be manufactured from a variety of raw materials that have a high percentage of carbon content and low impurities. They are characterized by a very high internal surface area. The selected carbon employed in two adsorption vessel for H_2S removal is produced by steam activation from selected grades of coal and impregnated with potassium bicarbonate. In the four tanks dedicated to siloxanes and VOCs removal, non-impregnated steam activated carbon produce from coal are used. The amount of filtering media needed per bed has been calculated scaling data from [53] as a function of biogas flow rate. Some parameters affect quantity of filtering media used, such as operative temperature and pressure and level of purification pursued.

The other mechanical components of the biogas processing system and of the heat recovery section are considered in terms of equivalent amount of reinforced steel. For the SOFCs CHP system a specific weight of 200 kg of steel per installed electric kW is taken from [49]. Making difference with the weight of C50 modules, the BoP result composed by around 16.8 tons of reinforced steel. Electric system is modelled with the number of inverters of 2.5 kW needed to reach total power (174 kW). Electrical and thermal energy required for CHP system production and assembly are taken from [49] and scaled based on the power plant size. As said, these rough simplifications are necessaries since specific data from manufacturers, or suitable datasets in databases for some components of the BoP, are not available.

4.3 CHP system maintenance

In this life cycle phase, all the necessary replacement of components and materials are considered. It is assumed a lifetime for the SOFCs of six years, so a substitution of 1/6 of the stacks is required each year. Concerning the activated carbons, each adsorption vessel in lead position saturates, with the contaminants level measured in the WWTP biogas, in six months, this means that two replacements per year are required. The catalysts of SR and WGS reactors are entirely replaced every four years. Other maintenance requirements (e.g. malfunctioning parts, occasional damages) are modelled as substitution of steel corresponding to 1% of the total mass in the system. Primary data are reported in Table 6.

Material/energy flows	Value	Unit
Stacks' replacement	3	pieces
Reinforced steel	262	kg
Stainless steel	66	kg
Steam reforming catalyst	13	kg
WGS catalyst	13	kg
Activated carbon, siloxanes + VOCs	1300	kg
Activated carbon, H_2S	650	kg

Table 6. Maintenance of the SOFC based CHP system. Reference flow: maintenance interventions in one year.

4.4 CHP system operation

Reference flows are thermal and electrical energy produced by SOFC modules in one year. Since the CHP system was not operative when the analysis was performed, the simulation of plant performance is performed through a tailored energy planner tool [54]–[56]. The installation in the WWTP of a SOFC CHP system implies the determination of a smart and efficient management of biogas stored in the gas holder. For the scope of this work, it is enough to say that the primary aim is to avoid fuel shortages and to minimize SOFC shut downs during the year. This goal is reached by means of a regulation of the SOFC power output according to the monitoring of the gas holder level. In Table 7 the most important operative parameters, obtained from the simulation, associated to the three SOFC modules, are reported. In the calculations, a constant percentage of methane of 60% is considered in the biogas and a corresponding lower heating value of 21.5 MJ/Nm^3.

SOFC modules		
Nominal electrical power	174	kW_{el}
Nominal biogas flow rate	55	Nm^3/h
Equivalent capacity factor	95	%
Number of shut downs	0	/
Avg. biogas flow rate	52.3	Nm^3/h
Effective electrical power	166.2	kW_{el}
Thermal power	81.1	kW_{th}
Avg. electrical efficiency	53.1	%
Avg. thermal efficiency	25.8	%
Annual operating hours	8581	h

Table 7. SOFC modules, outputs of the energy planner tool [54].

The multi-functionality issue associated to the production of heat and electricity by the CHP units is solved through the allocation based on exergetic contents of these streams. In Table 8 the inventory associated to CHP system operations is showed. The amount of system necessary for one year of operation is calculated as the inverse of plant lifetime, assumed of 20 years.

Material/energy flows	**Value**	**Unit**
Biogas to SOFC	449’084	Nm^3
DEMOSOFC system	0.05	pieces
DEMOSOFC maintenance	1	pieces
Emission to air		
Carbon dioxide, biogenic	880.8	ton

Table 8. Operative phase of the SOFC based CHP system. Reference flows: 1427 MWh electricity and 693 MWh heat (1 year of operation).

4.5 Boilers operation

As already said, thermal energy is requested to maintain the anaerobic digester in an optimal range of temperatures, in order to maximize biogas yield of the process. The exhaust gas analysis, and so the emissions associated to combustion, have been provided directly from maintainers of the plant. The amount of biogas and natural gas (NG) burned in boilers changes among different scenarios, so separated inventories have been produced in

1st case study *Reference flow : 3006 MWh heat*		
Material/energy flows	**Value**	**Unit**
Natural gas, IT mix	25’610	Nm^3
Biogas to boilers	518’408	Nm^3
Emission to air		
Carbon dioxide, biogenic	1020.2	ton
Carbon dioxide, fossil	50.5	ton
Carbon monoxide, biogenic	186.9	kg
Carbon, monoxide, fossil	15.4	kg
Nitrogen oxide	181.7	kg
Nitrogen dioxide	15.1	kg
2nd case study *Reference flow: 2256.3 MWh heat*		
Material/energy flows	**Value**	**Unit**
Natural gas, IT mix	155’317	Nm^3
Biogas to boilers	172’241	Nm^3
Emission to air		

Carbon dioxide, biogenic	338.9	ton
Carbon dioxide, fossil	306.0	ton
Carbon monoxide, biogenic	62.1	kg
Carbon, monoxide, fossil	93.3	kg
Nitrogen oxide	139.6	kg
Nitrogen dioxide	11.6	kg
3rd case study *Reference flow: 925.4 MWh heat*		
Material/energy flows	**Value**	**Unit**
Natural gas, IT mix	0	Nm^3
Biogas to boilers	172’241	Nm^3
Emission to air		
Carbon dioxide, biogenic	338.9	ton
Carbon dioxide, fossil	\	\
Carbon monoxide, biogenic	62.1	kg
Carbon, monoxide, fossil	\	\
Nitrogen oxide	55.8	kg
Nitrogen dioxide	4.6	kg

Table 9. The common reference flow is the amount of heat delivered in one year of operation.

1st case study *Reference flow : 3006 MWh heat*		
Material/energy flows	**Value**	**Unit**
Natural gas, IT mix	25’610	Nm^3
Biogas to boilers	518’408	Nm^3
Emission to air		
Carbon dioxide, biogenic	1020.2	ton
Carbon dioxide, fossil	50.5	ton
Carbon monoxide, biogenic	186.9	kg
Carbon, monoxide, fossil	15.4	kg
Nitrogen oxide	181.7	kg
Nitrogen dioxide	15.1	kg
2nd case study *Reference flow: 2256.3 MWh heat*		
Material/energy flows	**Value**	**Unit**
Natural gas, IT mix	155’317	Nm^3
Biogas to boilers	172’241	Nm^3
Emission to air		
Carbon dioxide, biogenic	338.9	ton
Carbon dioxide, fossil	306.0	ton
Carbon monoxide, biogenic	62.1	kg

Carbon, monoxide, fossil	93.3	kg
Nitrogen oxide	139.6	kg
Nitrogen dioxide	11.6	kg
3rd case study *Reference flow: 925.4 MWh heat*		
Material/energy flows	**Value**	**Unit**
Natural gas, IT mix	0	Nm^3
Biogas to boilers	172’241	Nm^3
Emission to air		
Carbon dioxide, biogenic	338.9	ton
Carbon dioxide, fossil	\	\
Carbon monoxide, biogenic	62.1	kg
Carbon, monoxide, fossil	\	\
Nitrogen oxide	55.8	kg
Nitrogen dioxide	4.6	kg

Table 9. Operative phase of the boilers (primary data from data collection at the WWTP site).

4.6 Anaerobic digester operation

The digestion process requires thermal energy, but also electricity for sludge mixing and recirculation.

The processes to which wastewater is subjected to obtain raw sludge, as well as the subsequent treatment of digested matter, are outside of the boundaries of the study since they are common phases of different scenarios. Carbon dioxide and methane emissions are due to leakage of pipes during the process and are assumed to be 0.75% of produced biogas according to [57]. The reference flow is the annual produced biogas; collected data are reported in

1st case study *Reference flow: 627041 Nm^3 biogas*		
Material/energy flows	**Value**	**Unit**
Heat, from boiler operation	3’006	MWh
Electricity, IT mix, from grid	158	MWh
Lubricating oil, at plant	178.6	kg
Emission to air		
Carbon dioxide, biogenic	3’715	kg
Methane, biogenic	2’022	kg
2nd case study *Reference flow: 627041 Nm^3 biogas*		
Material/energy flows	**Value**	**Unit**
Heat from boilers operation	2’256.3	MWh

Heat from SOFC	693.1	MWh
Electricity, IT mix, from grid	158	MWh
Lubricating oil, at plant	178.6	kg
Emission to air		
Carbon dioxide, biogenic	3715	kg
Methane, biogenic	2022	kg
3rd case study *Reference flow: 627041 Nm^3 biogas*		
Material/energy flows	**Value**	**Unit**
Heat from boilers operation	925.4	MWh_t
Heat from SOFC	693.1	MWh_t
Electricity, IT mix, from grid	171	MWh_e
Lubricating oil, at plant	178.6	kg
Emission to air		
Carbon dioxide, biogenic	3’715	kg
Methane, biogenic	2’022	kg

Table 10.

1st case study *Reference flow: 627041 Nm^3 biogas*		
Material/energy flows	**Value**	**Unit**
Heat, from boiler operation	3’006	MWh
Electricity, IT mix, from grid	158	MWh
Lubricating oil, at plant	178.6	kg
Emission to air		
Carbon dioxide, biogenic	3’715	kg
Methane, biogenic	2’022	kg
2nd case study *Reference flow: 627041 Nm^3 biogas*		
Material/energy flows	**Value**	**Unit**
Heat from boilers operation	2’256.3	MWh
Heat from SOFC	693.1	MWh
Electricity, IT mix, from grid	158	MWh
Lubricating oil, at plant	178.6	kg
Emission to air		
Carbon dioxide, biogenic	3715	kg
Methane, biogenic	2022	kg
3rd case study *Reference flow: 627041 Nm^3 biogas*		

Material/energy flows	Value	Unit
Heat from boilers operation	925.4	MWh_t
Heat from SOFC	693.1	MWh_t
Electricity, IT mix, from grid	171	MWh_e
Lubricating oil, at plant	178.6	kg
Emission to air		
Carbon dioxide, biogenic	3’715	kg
Methane, biogenic	2’022	kg

Table 10. Operative phase of the anaerobic digester (primary data from data collection at the WWTP site).

4.7 WWTP operation

This unit process includes electrical consumptions associated to plant operations, and emissions associated to biogas in excess, which is flared. It is assumed that the whole amount of methane flared is oxidized and converted in carbon dioxide (and water), since no specific information on emissions are available. The functional unit is the amount of wastewater treated by the WWTP in one year; collected data are reported in Table 11.

1st case study *Reference flow: 13’958’807 m^3 treated wastewater*		
Material/energy flows	**Value**	**Unit**
Electricity, IT mix, from grid	5’479.4	MWh
Biogas flared	103’930	Nm^3
Emission to air		
Carbon dioxide, biogenic	204.1	ton
2nd case study *Reference flow: 13’958’807 idem m^3 treated wastewater*		
Material/energy flows	**Value**	**Unit**
Electricity, IT mix, from grid	4’078	MWh
Electricity from SOFC	1’427	MWh
Biogas flared	1’008	Nm^3
Emission to air		
Carbon dioxide, biogenic	1.98	ton
3rd case study *Reference flow: 13’958’807 idem m^3 treated wastewater*		
Material/energy flows	**Value**	**Unit**
Electricity, IT mix, from grid	4’078	MWh
Electricity from SOFC	1’427	MWh
Biogas flared	1’008	Nm^3

Emission to air		
Carbon dioxide, biogenic	1.98	ton

Table 11. Operative phase of the WWTP (primary data from data collection at the WWTP site).

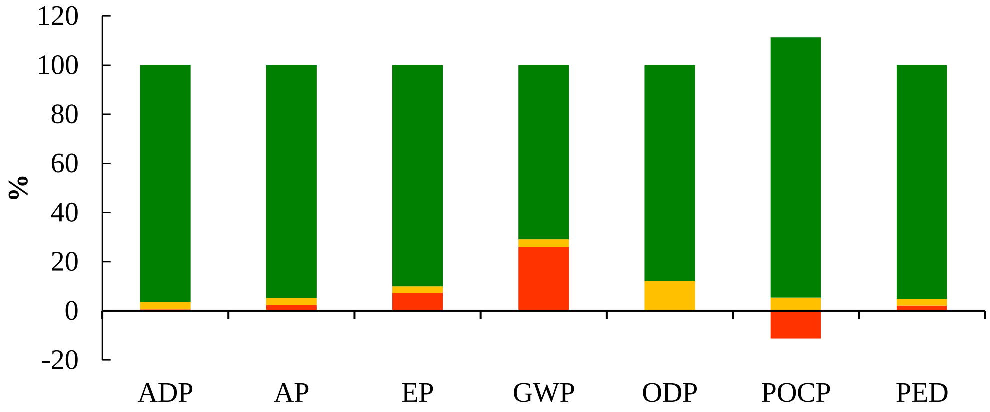
5. Results and discussion

The first step necessary for the interpretation of the results is the analysis of the LCIA profiles of different scenarios, in order to understand what life cycle phases, unit processes and flows have significant impact in the different categories and why.

5.1 Energetic flows and LCIA profiles

Energy flow referred to the three analysed scenarios are provided in Appendix A. In the reference scenario biogas handle, has yet noted, is not optimized since a relevant amount is flared without producing useful effects. Looking at the LCIA profile in Figure 7-a, it is clear that the process called WWTP operation gives the highest contribution in all the impact categories. This is due to the big amount of electricity needed by the plant for its operations.

a) Scenario 1 (reference)



b) Scenario 2

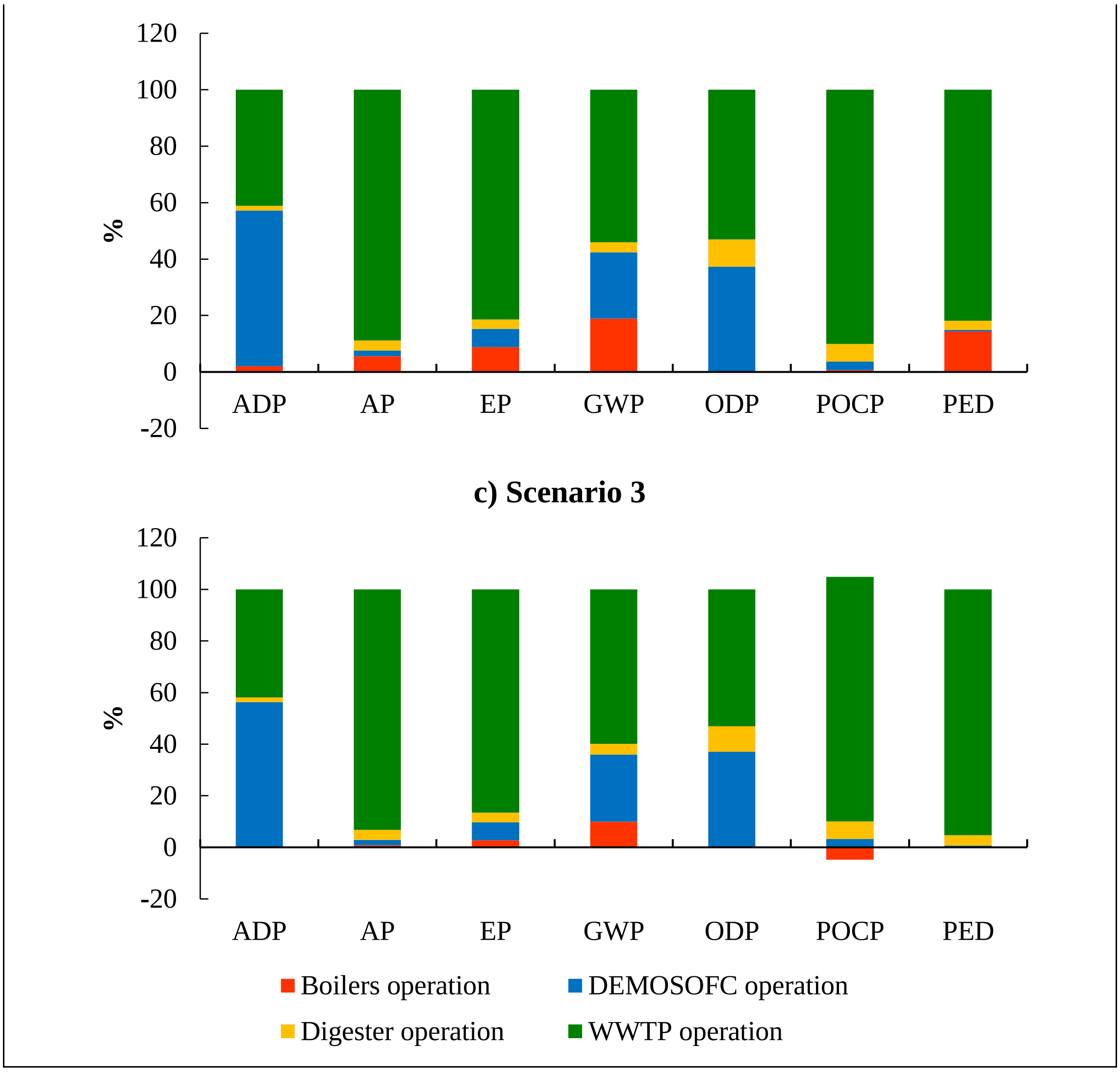


Figure 7. LCIA profile of the three scenarios.

Italian consumption mixes of electricity and natural gas of 2009 (last update available in the software) have been used for this evaluation. The electricity flow includes production, transport and mix of energy carriers, conversion processes in power plants and final transmission. In the GWP category, the operation of boilers gives an important contribution of around 26%, which is mainly attributable to emissions of carbon dioxide during the combustion process. The negative share (avoided impact) of boilers in the POCP category is determined by the negative contribution of NO emissions which play a predominant role.

In the second scenario, the LCA model shows how an improvement in biogas management with a reduction in the amount of primary resource flared (from 16.6 to 0.2%). Furthermore, a predominant amount of biogas (around 72%) is used in the CHP system in order to produce first electrical energy and then heat by means of a thermal recovery from the exhaust gases. As can be seen in Figure 7-b, even in this case the process called WWTP operation has a major role in all the impact categories except the ADP. Nevertheless all the shares associated to this process are reduced in comparison to the first scenario, because a portion of the electrical energy is produced by the SOFC CHP system. The ADP of elements is prevalently linked to the change of infrastructure in the WWTP and so to the manufacture and maintenance of the cogeneration system. Steel and copper are the materials used in larger amounts which have predominant influence on this category. GWP and ODP are also heavily affected by the installation and operations of the CHP units. In the first, the results are linked to a different biogas handling, which is mainly used for electricity production in SOFC modules where methane is oxidized to carbon dioxide through SR and WGS reactions. In the second, the manufacturing and maintenance phases give almost 37% of contribution and main sources of ozone depleting substances are the processes of production of steel, copper and materials of the EEA (such as nickel oxide, LSM and YSZ). In the PED the contribution of the operative phase of boilers increase up to 14% since, in this scenario, the thermal energy generated from biogas decreases and consequently a higher consumption of NG is necessary to satisfy the digester demand.

In the third scenario, the reduction of thermal demand for the digestion process is a consequence of the increase in the level of pre-thickening of sludge up to 6.4% wt., thanks to the installation of the dynamic machine. As yet said this is the level of organic dry matter inside the sludge which allows the WWTP to be independent from natural gas. The slight increase in electricity consumption in the process called digester operation is owed to absorptions of the dynamic machine.

In Figure 7-c, the LCIA profile of this scenario is reported. Main differences respect to the second scenario arises in GWP and PED concerning the operative phase of boilers. The primary energy demand associated to this process is null, since no external resources are employed and the decrease of GWP is attributable to a lower production of heat and related emissions.

5.2 Interpretation of results and comparison between the assessed scenarios

The second step in the interpretation of results is the cross-comparison of obtained LCIA profiles for the three scenarios. As shown in Figure 8, the impact of the second and third scenarios is lower than in the reference case in five of the seven impact categories analysed. To better understand these outputs and facilitate the comparisons, processes involved in the analysis are grouped in five sections:

- **Heat from SOFC**: Allocation based on exergy (*8.1 %* of the operative phase of the CHP system)
- **Heat from boilers**: Natural gas and biogas consumption and combustion's emissions
- **Digester**: Electricity and lubricating oil for its operation, flare and pipe leakage emissions
- **Electricity from SOFC**: Allocation based on exergy (91.9 % of the operative phase of the CHP system)
- **Electricity from grid**: Electricity required by the WWTP (excluded those auto-produced from SOFC)

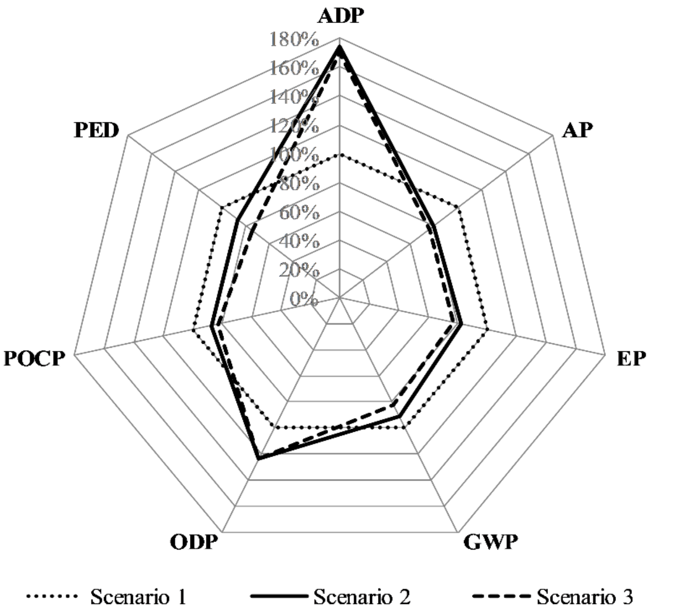


Figure 8. Impact assessment results.

The ADP of elements is higher in the WWTP with the cogeneration system installed. This fact is not unexpected since the manufacture and maintenance of many components is included in these scenarios. Looking at Figure 9-a, the ADP of electricity produced from the SOFC modules is higher than that associated to electricity withdrawn from the grid since the total amount of electrical energy required in all the scenarios is almost the same (in the CHP systems a slight increase of consumed energy is owed to the balance of plant's absorptions). The ADP associated to heat from boilers in the third scenario is null thanks to the reached independence from natural gas.

The AP (Figure 9-b) in the second and third scenarios is reduced by 20.6% and 24.2% respectively, compared to the reference. Electricity produced from the CHP units is significantly less impacting than that purchased from the grid. This is due to the fact that during the life cycle phases of manufacture, maintenance and operation of the cogeneration system few emissions of substances with a high AP (e.g. SO_2 and NO_x) occur. Among the processes with a higher specific AP there is the use of nickel, needed for EEA and catalyst manufacture. The AP of heat produced in boilers is strictly associated to the use of natural gas for its production.

A reduction of the EP (Figure 9-c) by 17.7% compared to the reference case is obtained with the CHP system, and by 22.6% if also dynamic pre-thickening of sludge is performed. The self-produced electricity has a lower impact than that withdrawn from the grid. Concerning EP of thermal energy produced by boilers. Its value is primarily linked to nitrous oxide emissions associated to the combustion process. In fact, in the third scenario, in which a lower amount of heat is produced through combustion, the EP decreases.

GWP (Figure 9-d) is reduced by 9% in the second scenario. This impact indicator is connected to the greenhouse gases emissions associated predominantly to operative phases of the life cycle. Therefore advantages are associated to the primary energy savings measures adopted: better biogas management (only 0.2% is flared) and installation of the CHP system which avoid separate generation of a significant fraction of energy. The further thermal energy saving opportunity identified in the third scenario allows a reduction by 18% of GWP compared to the reference scenario.

The ODP (Figure 9-e) of the two CHP scenarios increase by 23.6 % compared to the reference WWTP. Here manufacture and maintenance phases play an important role; in particular nickel and LSM production gives the highest specific contributions. As a result, the electricity produced from SOFC modules has a higher ODP than that from the Italian mix.

The POCP (Figure 9-f) is primarily linked to the operative phase of the WWTP. Since the SOFC based CHP system has negligible emissions of VOCs and NO_x, the electricity produced has a lower impact than that withdrawn from the grid. The negative contributions in the histogram are owed to the NO emissions from combustion in boilers (which promote tropospheric ozone decomposition in NO_2 and O_2). The emissions of substances which promote bad-O_3 formation during the supply of natural gas (e.g. during extraction and transport processes) are annulled in the third scenario due to NG independence.

PED (Figure 9-g) associated to the manufacture and maintenance of the CHP units is very low if compared to that needed during system operations. This is a quite common situation in life cycle assessments of energy systems. As a consequence the contributions to PED associated to heat and electricity produced from SOFC modules are imperceptible in Fig. 21. The second and third scenarios allows a reduction by 13.5% and by 25.7% of PED respectively. In the third scenario, the decrease in PED associated to the annulment of natural gas consumption prevails over its increase during operations of the dynamic machine.

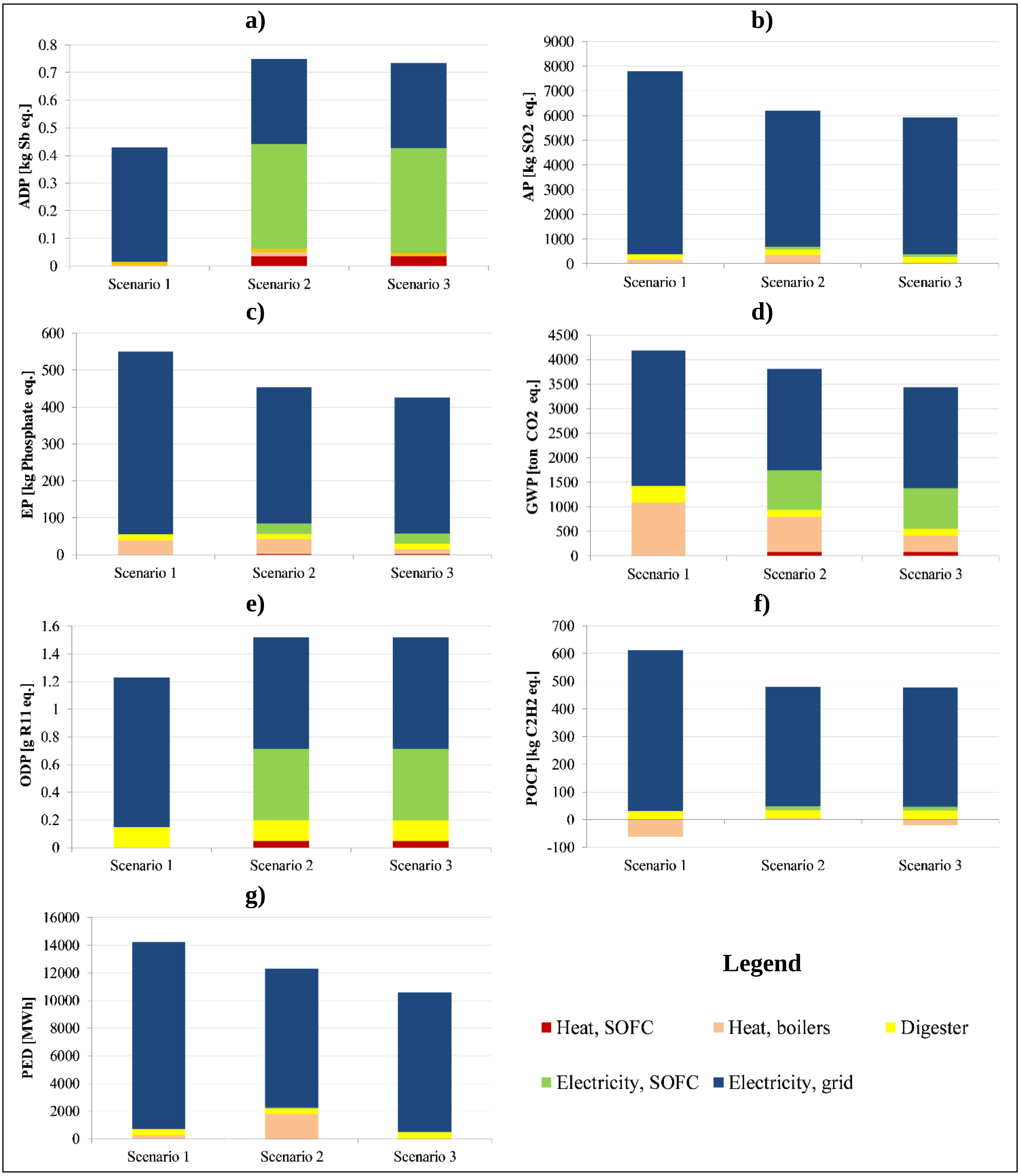


Figure 9. Impact categories results for the three analysed scenarios.

5.3 Energy and Carbon payback times

Energy and carbon payback times have been calculated dividing the embodied energy/CO_2 emissions in the manufacture and maintenance of the system by the net annual energy/CO_2 emissions savings due to the operation of the CHP units in the second and third scenario. Embodied energy/CO_2 emissions in the manufacture and maintenance of the system are 5002 GJ and 227 tonCO_2 for the entire plant lifetime (20 years). Emissions savings due to the operation of the CHP units are, for Scenario 2, 7’147 GJ/y and 421 tonCO_2/y; for Scenario 3, 13’405 GJ/y and 771 tonCO_2/y. Results are reported in Table 12, referred in this chapter to IT energy mix.

PBT [years]	2nd case study	3rd case study
Energy	0.70	0.37
Carbon	0.54	0.29
Sensitivity analysis		
Energy, IT mix	0.70	0.37
Energy, EU mix	0.63	0.36
Carbon, IT mix	0.54	0.29
Carbon, EU mix	0.56	0.31

Table 12. Payback times and sensitivity analysis on IT and EU energy mix.

5.4 Sensitivity analysis

In the last part of this study a sensitivity analysis is performed, with the aim of determining how much changes in the electricity consumption and in the natural gas supply mix can affect results of the impact assessment (environmental impact and sustainability indicators). Attention is focused on these energetic flows since the analysis of the LCIA profiles of the different scenarios has stressed their important contribution in all the impact categories. The Italian mix previously employed is substituted with the EU-27 mix in order to represent a general situation not affected by the peculiarities of a specific energetic portfolio. In Figure 10 the mixes relative to the year 2009 (last update available), used in the Ecoinvent database, are reported. Concerning the production of electricity in the Italian mix, a higher penetration of renewable resources (even if a substantial share is associated to hydro) and a larger use of natural gas can be observed. Instead, the EU-27 mix is characterized by a diffused use of coal and a significant nuclear production; together these sources represent more than half of electrical consumptions. In Italy natural gas is predominantly supplied by Algeria, Russia, Libya and a significant share is also auto-produced (around 10%) while in the EU-27 major contributions to the supply mix come from Netherlands, Russia, Norway and UK.

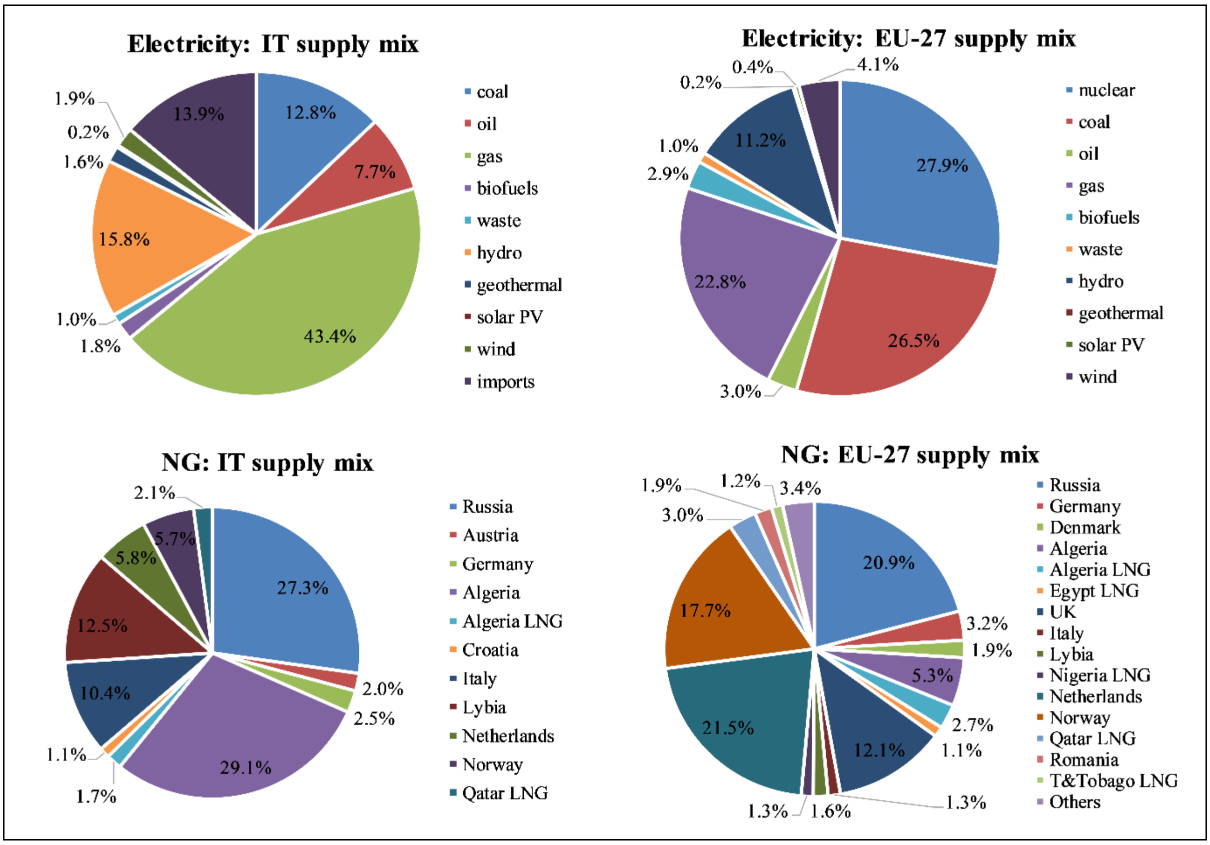


Figure 10. Energetic mixes used for the sensitivity analysis.

In Figure 11 the results of impact assessment comparing EU-27 and Italian mixes for the second and third scenario are represented. Potential impacts obtained using Italian mixes are lower in five of the seven analyzed impact categories, and major advantages arise for ODP and AP. The WWTP in the third scenario does not need natural gas, so it is not sensitive to variation associated to this flow. Since the trend for both scenarios is comparable, it can be said that LCIA results are more sensitive to variation in the electricity mix than in the natural gas mix. This fact is in agreement with the high electrical demand of the WWTP, but also underlines the importance that renewable nature of electricity has in a life cycle assessment.

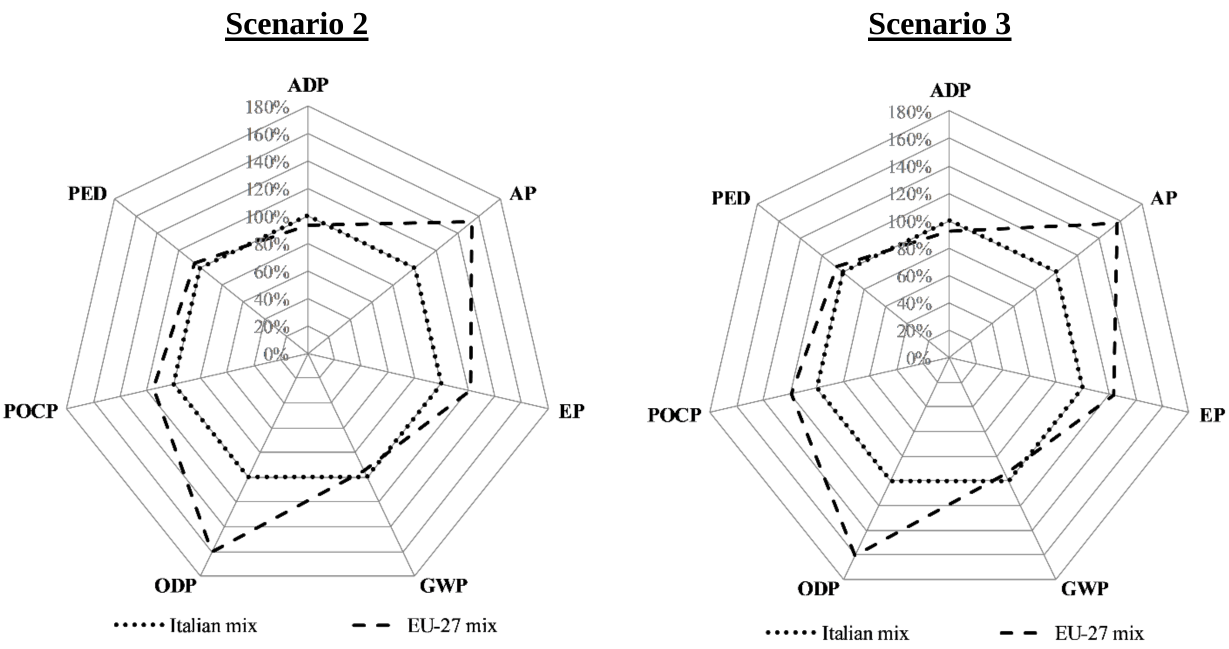


Figure 11. Sensitivity analysis of the second and third scenario.

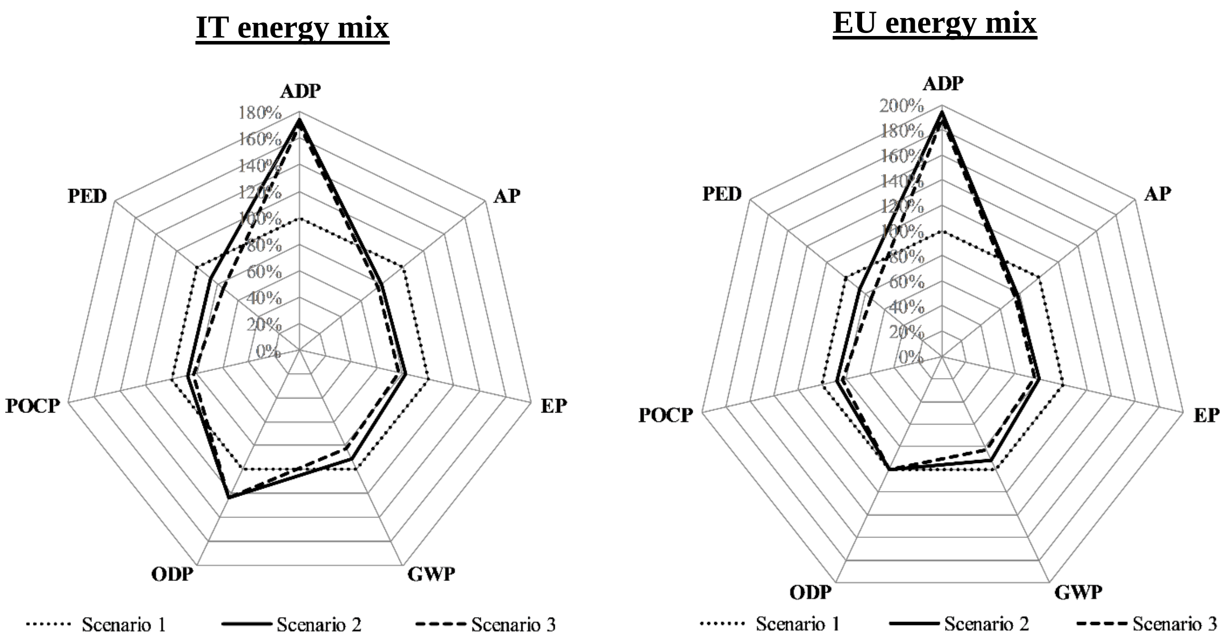


Figure 12. Impact categories in reference to the first scenario with EU-27 and Italian mix.

Finally in Figure 12 are reported results of the second and third scenarios with respect to the reference one using the energetic mixes previously introduced. The trends are very similar except for ODP category which becomes slightly smaller than in the first scenario if EU-27 mixes are used. Energy and carbon payback times are low sensitive to variation in energetic mixes (Table 12).

6. Conclusions

The analysis has been focused on three alternative scenarios for biogas exploitation in a medium size waste water treatment plant. Real industrial plant data have been retrieved from the DEMOSOFC project for what concerning the operation phase and the SOFC management.

The first, the “reference” scenario (scenario 1), in which all the electricity needed for operations is purchased from the grid and biogas handling has shown the poorest performances . The second scenario (scenario 2), which foresees the installation of the SOFCs CHP system and biogas management improvements has shown intermediate performance. The third scenario (scenario 3), in which biogas handling is further optimized through the reduction of thermal demand of the anaerobic digester by means of a dynamic pre-thickening machine for sludge is the best performing.

The large amount of electricity required for WWTP operations urges for a recovery of the renewable biogas, which is largely available on-site, and can satisfy a large part of this demand. Through the use of the life cycle methodology, the potential reduction of the environmental burdens of a WWTP, in which efficient SOFC based CHP modules are installed, is assessed. A thermal energy conservation opportunity that foresees the use of a dynamic machine for sludge pre-thickening enhancement is also investigated.

The operative phase of the analysed components inside the WWTP has proven to be determinant in all the impact category analysed. The depletion of non-renewable resources (ADP) is primarily linked to the manufacture and maintenance of the cogeneration units and of the tailored balance of plant. In the first scenario, a predominant part of the impact in all the categories is associated to the electricity withdrawn from the grid. The LCIA has showed that producing a substantial share of electrical energy (around 25%), through the installation of SOFC based cogeneration modules that are fed by the on-site available renewable resource, can reduce environmental burdens associated to WWTP operations in five of the seven impact category analysed: AP, EP, GWP, POCP and PED. A further reduction of impacts, particularly concerning GWP and PED, is possible through the reduction of the thermal demand of the digester, making the system independent from natural gas. In both second and third scenarios, primary energy and CO_2 emissions embodied in the manufacture and maintenance of the CHP system are neutralized by operative savings in less than one year.

The sensitivity of LCIA outputs to a variation of electricity consumption and natural gas supply mixes is relevant mainly in the regional impact categories AP, EP and POCP, but also in global ODP. In particular, the EU-27 mix has a higher impact than the Italian one because a larger dependence on more polluting fossil sources (coal is still employed in large quantities) and nuclear has been highlighted. It is worth to remember that data of energetic mixes available in the software are of 2009 and in the meanwhile significant changes occurred. Nevertheless, it can be said that the quality of produced electricity, measured in terms of its renewable origins, plays a decisive role in life cycle assessment of energy intensive systems. Positive effect on environmental loads of second and third scenarios are confirmed when the EU-27 mixes are used; furthermore a slightly reduction of ODP, compared to the first scenario, is obtained.

Main limits associated to this study are low availability of specific data concerning manufacturing and maintenance phases of the balance of plant that makes necessary the use of some rough assumptions, and the exclusion from the boundaries of the work of end of life scenarios (e.g. recycle or disposal of materials) due to lack of usable information. Anyway, the model could be further refined and improved for future studies.

Pursue of electrical and thermal self-sufficiency of WWTPs through the installation of efficient cogeneration systems, and the careful evaluation of energy conservation opportunities both in sludge and water lines seem to go in the right direction towards a better environmental sustainability.

Acknowledgments

Please refer to this published work [58] if you want to cite the present document and the information here included. In the publication, supplementary material on the inventory is also available.

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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.