# Techno-economic assessment of biogas-fed solid oxide fuel cell combined heat and power system at industrial scale

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**Abstract**

Wastewater treatment plants (WWTP) are currently very energy and greenhouse gas intensive processes. An important opportunity to reduce both of these quantities is via the use of biogas produced within the treatment process to generate energy. This paper studies the optimal energy and economic performance of a wastewater treatment facility fitted with a solid oxide fuel cell (SOFC) based combined heat and power (CHP) plant. An optimisation framework is formulated and then applied to determine cost, energy and emissions performance of the retrofitted system when compared with conventional alternatives.

Results show that present-day capital costs of SOFC technology mean that it does not quite compete with the conventional alternatives. But, it could become interesting if implemented in thermally-optimised WWTP systems. This would increase the SOFC manufacturing volumes and drive a reduction of capital and fixed operating costs.

*Keywords:* solid oxide fuel cells, biogas, optimisation, waste water treatment

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## 1. Nomenclature

### *1.1. Symbols*

**Acronyms**

| | |
|---|---|
| $AC$ | alternating current |
| $CHP$ | combined heat and power |
| $EAC$ | equivalent annual cost |
| $EP$ | equivalent person |
| $GT$ | gas turbine |
| $LCOE$ | levelized cost of electricity |
| $MGT$ | micro gas turbine |
| $ICE$ | internal combustion engine |
| $MILP$ | mixed integer linear programming |
| $MINLP$ | mixed integer nonlinear programming |
| $NG$ | natural gas |
| $NLP$ | nonlinear programming |
| $PEMFC$ | proton exchange membrane fuel cell |
| $RDD\&D$ | research, development, demonstration, and deployment |
| $sLCOE$ | system levelized cost of electricity |
| $SOFC$ | solid-oxide fuel cell |
| $TSS$ | total suspended solids |
| $WWTP$ | wastewater treatment plant |

**Sets**

| | |
|---|---|
| $f \in F$ | fuel cells, $F$ = {f1, . . . , fn} |
| $r \in R$ | regimes, R = {r1, r2} |
| $t, tt \in T$ | periods, T = {t1, . . . , t8760} |
| $dot \subset T$ | minimum hours for shut-down event, dot={t+1, . . . , t+td-1} |
| $upt \subset T$ | minimum hours for start-up event, upt={t+1, . . . , t+tup-1} |
| $u \subset U$ | set of clean-up utilities, $U$ = {u1, . . . , un} |

**Parameters**

| | |
|---|---|
| $af$ | annualisation factor |
| $BCap$ | boiler capacity, kWh |
| $BGi_t$ | biogas flow inlet, kWh |
| $BGSabs$ | biogas absorbed per start up event, kWh |
| $BGDabs$ | biogas absorbed per shut down event, kWh |
| $DTL_t$ | system thermal load per time $t$, kWh |
| $Ed_t$ | WWTP electricity demand at time $t$, kWh |
| $\epsilon_r^{fb}$ | electrical efficiency of generator $f$ from biogas per regime $r$ |
| $\epsilon_r^{fn}$ | electrical efficiency of generator $f$ from natural gas per regime $r$ |
| $\eta^b$ | boiler thermal efficiency, |
| $\eta_r^{fb}$ | thermal efficiency of generator $f$ from biogas per regime $r$ |
| $\eta_r^{fn}$ | thermal efficiency of generator $f$ from natural gas per regime $r$ |
| $cp$ | carbon price, € per kg$CO_2$ |
| $GHL$ | gas holder lower volume limit, kWh |
| $GHU$ | gas holder upper volume limit, kWh |
| $i$ | interest rate |
| $r_{up}$ | ramp modulation, kWh |
| $ee$ | electricity emission factor, kg$CO_2$ per kWh |
| $ep_t$ | electricity price at time $t$, € per kWh |
| $ge$ | natural gas emission factor, kg$CO_2$ per kWh |
| $gp_t$ | natural gas price at time $t$, € per kWh |
| $n$ | number of generators |
| $ND$ | number of years for the investment to be written off |
| $oCAPEX$ | overnight capital expenditure, € |
| $oRC$ | overnight replacement costs, € |
| $Pnom$ | generator nameplate capacity, kWh |

| | |
|---|---|
| $PRU_r$ | maximum electric output per generator regime $r$, kWh |
| $PRL_r$ | minimum electric output per generator regime $r$, kWh |
| $UCC$ | unit capital costs |
| $URC$ | unit replacement costs |
| $td$ | generator minimum down time, hours |
| $tup$ | generator minimum up time, hours |
| $UEC_u$ | unit energy consumption of utility $u$ |
| $UMC$ | annual maintenance cost per generator, € per kWh |
| $UMCb$ | annual maintenance cost of boiler, € per kWh |
| $UOC$ | annual clean up cost per generator, € per kWh |
| $PSUabs$ | average power absorbed per start up event, kW |
| $PSDabs$ | average power absorbed per shut down event, kW |

**Decision variables**

| | |
|---|---|
| $BGb_t$ | biogas fuelled into boiler at time $t$, kWh |
| $BGCHP_t$ | biogas fuelled into CHP units at time $t$, kWh |
| $BGD_{t,f}$ | biogas flow absorbed for shut-down at time $t$ of generator $f$, kWh |
| $BGn_t$ | biogas flow not exploited at time $t$, kWh |
| $BGS_{t,f}$ | biogas flow absorbed for start-up at time $t$ of generator $f$, kWh |
| $CHPT_t$ | thermal output from all the generators at time $t$, kWh |
| $CHPE_t$ | electrical output from all the generators at time $t$, kWh |
| $Ei_t$ | electricity bought from grid at time $t$, kWh |
| $GH_t$ | gas holder level at time $t$, kWh |
| $NGb_t$ | natural gas fuelled into boiler at time $t$, kWh |
| $NGD_t$ | total natural gas consumed at time $t$, kWh |
| $PSD_{t,f}$ | electricity absorbed for shut down of generator $f$ at time $t$, kWh |
| $PSS_{t,f}$ | electricity absorbed at start up of generator $f$ at time $t$, kWh |
| $\upsilon_{t,f}$ | binary equal to 0 if generator $f$ at time $t$ is switched off, to 1 if switched on |
| $\chi_{t,r,f}$ | binary equal to 1 if at time $t$ generator $f$ operates at regime $r$, 0 if switched off |
| $X_{t,r,f}$ | electrical output of generator $f$ per regime $r$ and time $t$, kWh |
| $Xb_{t,r,f}$ | electrical output from biogas of generator $f$ per regime $r$ and time $t$, kWh |
| $Xn_{t,r,f}$ | electrical output from natural gas of generator $f$ per regime $r$ and time $t$, kWh |

**Objective function variables**

| | |
|---|---|
| $TC$ | total annual cost of CHP system, €/year |

## 2. Introduction

Wastewater treatment is one of the most energy intensive public utilities, accounting for more than 1 % of electricity consumed in Europe (ENERWATER project, 2015). There are more than 23,000 wastewater treatment plants across Europe with at least secondary treatment (European Environment Agency, 2016b), with an overall energy consumption and greenhouse gas emissions of approximately 15,000 GWh/yr and 27 Mt$CO_2$-eq/yr, respectively (ENERWATER project, 2015) (European Environment Agency, 2016a). Reduction of the energy use and emissions is a worthwhile

part of broader deep decarbonisation strategies in place in Europe (European Commission, 2016).
A range of measures exist to reduce energy consumption in WWTPs, from simple options such as the adoption of more efficient mechanical devices, through to the use of possibilities such as anaerobic granular sludge technology (Pronk et al., 2015). Alternatively, processes that convert sludge into biogas using anaerobic digestion, followed by use of the biogas to generate electricity and heat, are very promising. Technologies currently employed in this application are internal combustion engines (ICE) and microturbines (MGT). Medium-scale fuel cells are also a promising option due to their high electrical efficiency and suitability for CHP applications. This latter technology, using solid oxide fuel cell (SOFC) technology ((Leone, 2014); (Tjaden et al., 2014); (Curletti et al., 2015)) is the main prime mover of interest in this article due to the ability to generate electricity in the efficiency range of 50 – 62 % (Curletti et al., 2015).
The use of SOFCs for combined heat and power in WWTPs is not without challenges. Biogas from the anaerobic digestion of mixed urban and industrial sludge contains several micro-contaminants, among which hydrogen sulphide ($H_2S$) and siloxanes can be very harmful for the fuel cell ((Papadias et al., 2012); (Madi et al., 2015)). As such, very effective gas clean-up is required. Also, biogas supply from the digester is variable on both daily and seasonal time scales, implying that modulation of the SOFC system may be desirable, which may in turn lead to accelerated degradation of the SOFC stack. However, perhaps the most important challenge is economic, where high capital costs of SOFC technology are often cited as a barrier.
This article focuses on the specific question of techno-economics, developing a framework and presenting an analysis on the case of a combined sludge digestion SOFC system at a WWTP. To the authors' knowledge this work represents the only contribution to the study of SOFC feasibility in sub-MW WWTPs based on a cost optimal dispatch model over a year of operation using real plant data. The following section presents more broadly the technical challenges of SOFC adoption in WWTPs as well as recent relevant research via a literature review. This is followed by a problem statement and mathematical formulation of an optimisation modelling approach for biogas-based cogeneration systems in sections 3 and 4. Finally the model is applied leading to discussion of key results and conclusions.

## 3. Literature review

### *3.1. Technical challenges of SOFC adoption*

The water-energy nexus principles promote technological RDD&D (research, development, demonstration, and deployment) plans for self-efficient WWTP facilities from the energy perspective (Department of Energy, 2014) (Rothausen & Conway, 2011). Despite relevant regional differences, WWTPs are generally far from meeting these targets. According to a recent review of 12 large

WWTPs with cogeneration from on-site produced biogas in Australia (Daw et al., 2012), specific net energy consumption reduced from 63.6 to 28.9 kWh/yr/EP (EP stands for equivalent person), which is impressive progress but still well short of net zero energy consumption.

Several options could be explored towards meeting the water-energy nexus targets, such as adoption of advanced sludge handling systems or more efficient prime mover for onsite CHP generation.

Concerning sludge handling, the adoption of aerobic granular sludge technology in WWTPs in the Netherlands has allowed attaining an energy consumption of only 13.9 kWh/yr/EP, which is about 58 – 63 % less than the average conventional activated sludge treatment plants (Pronk et al., 2015).

Concerning onsite power generation, benefits would be achieved promoting the conversion of biogas into more efficient combined heat and power technologies. State-of-the-art technologies like MGT and ICE can only display limited electrical efficiency overall: up to 28 – 30% with MGTs in small capacities and up to 40 % with ICEs in big capacities (i.e. above 0.5 – 1 MW (Lantz, 2012)). The adoption of SOFCs in WWTPs would have a dramatic impact on boosting the biogas conversion efficiencies in WWTPs as SOFCs can generate electricity with an efficiency in the interval 50 – 62 % (Curletti et al., 2015).

The feasibility of operating an SOFC with biogas has been widely investigated both in lab-environment ((Shiratori et al., 2008); (Lanzini & Leone, 2010); (Papurello et al., 2014a) (Papurello et al., 2014b); (Leone, 2014), (de Arespacochaga et al., 2015)) and prototype systems (Papurello et al., 2015). When exploiting sewage biogas for energy end-uses, one of the most significant issues is the quality of the feeding gas fuel. The $H_2S$ present in WWTP-biogas is detrimental for SOFCs as it rapidly deactivates the catalytic and electro-catalytic activity of the Ni-anode (Papurello et al., 2016). Siloxanes are a second class of compounds present in WWTP-biogas which can undergo a rapid thermal decomposition in the Ni-anode producing silica deposition on both stack metallic interconnects and the Ni-anode (Madi et al., 2016) causing rapid degradation of the cell even at small percentages (i.e. lower than 100 ppb by volume of D4-siloxane, octamethylcyclotetrasiloxane). Currently, adsorption on impregnated activated carbons is the most efficient and economical way to obtain an effective biogas clean-up and meet the requirements on biogas composition (Abatzoglou & Boivin, 2009).

In addition to the quality of the feeding gas, an SOFC-based CHP system operating in a WWTP must cope with a variable biogas supply throughout the year. This poses operating challenges both on a daily and seasonal time scale. Daily fluctuations are inherently related to the biological processes inside the digester and variations in quality and quantity of wastewater received by the plant. The seasonal trend is instead due to the overall amount of wastewater treated, which is significantly reduced in summer, particularly in July and August.

### *3.2. Modelling SOFCs and their applications*

High electrical efficiency, low emissions and wide range of applications, both for stationary and transportation purposes, make SOFCs one of the most suitable candidate technologies to promote more sustainable energy systems (Choudhury et al., 2013) (Ramadhani et al., 2017). Mathematical modelling has been instrumental in achieving the current state of development as well as in allowing the continuous improvement of the technology. Detailed accounts of the research efforts focused on optimising the SOFC design and geometric configurations were discussed in (Kakaç et al., 2007) and in (Hajimolana et al., 2011). In addition to the device-level research, modelling approaches have also been proposed to characterize fuel cell operations and integration within large systems. (Hawkes et al., 2006) proposed a cost minimisation model based on nonlinear programming (NLP) to simultaneously optimise capacity and operating variables of a residential micro-CHP system consisting of an SOFC stack, a power electronics module and a supplementary boiler. Concerning fuel cell integration on a large scale, (Koyama et al., 2004) modelled an SOFC/GT-based centralized power system in Japan (GT stands for gas turbine). They linked an SOFC/GT detailed model with a power generation capacity and dispatch optimisation model. The authors claimed that, although SOFC would represent a winning solution from the perspective of $CO_2$ emission reduction compared to existing technologies, high investment costs still represent a barrier to its deployment. (Pruitt et al., 2013) studied the retrofit of an existing commercial building with a CHP distributed generation system, consisting of photovoltaic cells, power-only and CHP SOFCs, lead-acid batteries, and a hot water storage tank. The authors proposed an optimisation model to determine the configuration, capacity, and operational schedule of the CHP system for meeting power and heat demands of a commercial building at the globally minimum total cost. The model envisaged technical operational aspects to capture detailed system performance. The final result is a large, nonconvex MINLP (mixed-integer nonlinear programming) model which was solved using purpose-devised solution algorithms. (Bang-Møller et al., 2011) modelled a hybrid plant where wood gasification was combined with an SOFC and gas turbine system for the co-production of heat and power. After process optimisation, the energetic net electrical efficiency increased from 55.0 % to 58.2 % and the exergetic net electrical efficiency from 47.6 % to 50.4 %. (Trendewicz & Braun, 2013) presented a detailed process modelling performed in Aspen Plus® of an SOFC-based CHP system for biogas utilization at WWTPs. The system techno-economic appraisal showed that SOFCs could offer an efficient way of utilizing biogas fuel at WWTPs and successfully compete with other co-generation technologies in this market if mature stack costs were realized. The local characteristics of biogas fuel, however, make the economics of CHP projects site-specific and highly variable. (Guan et al., 2014) studied the use of PEMFCs (proton exchange membrane fuel cell) in Aspen Plus® fed with reformate biogas for the co-generation of electricity and heat to a dairy farm - biogas plant system.

Recently, (Ramadhani et al., 2017) have provided a comprehensive review of optimization strategies involving SOFC applications. SOFC micro-generators conceived for residential use or small-scale commercial services are already quite well established applications. (Facci et al., 2017) evaluated the potential of a combined heating-cooling and power plant based on SOFCs in terms of economic, energy and environmental performance. They considered a hypothetical case study where the plant satisfies the energy demand of a residential cluster made of 10 apartments; they also analyzed different configurations of the trigeneration system. (Wakui et al., 2016) studied the operation management of a residential energy-supplying network where multiple co-generation units were used, such as polymer electrolyte fuel cells, solid oxide fuel cells as well as air-to-water heat pump units. They proposed an optimization model that hierarchically integrates energy demand prediction, operational planning and operational control.

A few studies addressed the SOFCs applied to industrial systems. (Wu et al., 2017) combined an optimization approach of a microalgae-to-biodiesel chain with the process simulation of the corresponding heat and power system based on an integrated co-gasification combined cycle. Specifically, the residual dry microalgae was co-gasified with coal and the corresponding syngas used to fuel an integrated SOFC-gas turbine combined cycle.

Finally, the contribution of the research to the integration of biogas obtained from anaerobic digestion into SOFCs only applies to very few steady state analyses for large scale systems. (Siefert & Litster, 2014) proposed a steady-state exergy and economic analysis of a 1 MW CHP plant which uses energy produced from a biogas-fuelled SOFC in an anaerobic digester. They studied the exergy cell efficiency, power normalized cost and the internal rate of return of the investment as a function of a series of operation conditions such as the current density, the stack pressure, the fuel utilization and the total air stoichiometric ratio. The technoeconomic study by (Hauptmeier et al., 2016) concludes that in the niche, but promising, market of biogas utilization in sewage plants there is a high potential for small-to-medium SOFCs.

To the authors knowledge there is no contribution in the literature assessing the feasibility of biogas-fueled SOFCs integrated into a real WWTP plant. The originality of the work is more broadly explained in the following. First, the approach uses an optimal dispatch model which assesses the minimum cost of the hourly operation of the energy provision system over a full year of operation. As such, not only daily and seasonal fluctuations of biogas availability are accounted for, but also the variations of prices of alternative energy carriers (i.e. imported natural gas and electricity from the grid) are considered in the way they would affect the cell capacity factor during real operations. Second, the use of plant data of biogas availability, thermal and electrical needs as well as cell performance, allows the assessment of the SOFC technical feasibility in a real system operation. In addition, the analysis is carried out for state-of-the-art technologies such as micro-turbine and internal combustion engine, thus determining the cost-effectiveness conditions of SOFCs against competitive devices. Third, this work assesses how the technical and economic feasibility for SOFCs in WWTPs would change against competitive engines when economies of scale cause further cost reductions. In view of this, the analysis identifies conditions for SOFCs applicability in WWTPs which provides a feedback to manufacturers and end-users about the major pros and cons of implementing the technology at a medium scale.

The studied system is a sub-MW WWTP retrofitted with a biogas-fed SOFC CHP plant which operates in parallel with electricity imported from the grid and a supplementary boiler, which can be fuelled with either natural gas or biogas. As such, the annual thermal and electrical loads of the WWTP can be met either using on-site heat and electricity generated from the SOFC-based CHP or exploiting the supplementary boiler and electricity bought from the grid. The methodology is based on an MILP (mixed integer linear programming) modelling approach, primarily developed to study the optimal commitment of biogas-fed SOFCs, but generically applicable to any number of units of CHP systems connected to a generic thermal and electrical load.

The problem is the optimal unit commitment of a 3-unit CHP system integrated to the sub-MW WWTP in Collegno (Turin, Italy), whose hourly profiles of the biogas, as well as of thermal and electrical loads were used in this work (SMAT, 2016). At every hour, the model, minimising the system operating costs, defines which fuel mix fulfils the thermal and electrical loads. Dynamics of CHP units are included imposing minimum up- and down-time as well as ramp rate constraints.

In order to analyse short-, medium- and long-term barriers to the SOFC deployment, first, a critical appraisal of the SOFC performance is made with respect to other state-of-the-art CHP technologies (i.e. ICE and MGT) whose optimal commitment is analysed by means of the same optimisation model. Second, sensitivity analyses are performed on key cost factors and pathways for technological learning on SOFC manufacturing are laid out.

The optimisation approach chosen can give relevant insights into medium scale-CHP commercialisation as an emerging technology, showing potentials and opportunities for improvements both for SOFC manufacturers and end-users. Manufacturers can investigate the impact of design decisions (i.e. scale), operating and technological variables (i.e. thermal and electrical output from SOFCs, minimum up- and down-time, ramp rates) on the commercialisation of their technology; end-users can assess opportunities and risks of adopting the technology in their business. The use of real input data also provides a unique added value to the work.

## 4. Problem statement

This work uses a cost optimal unit commitment model for the techno-economic appraisal of the retrofitting of the sub-MW Collegno WWTP managed by SMAT in Turin (SMAT, 2016). A simplified representation of retrofitting project is in Figure 1. It involves the installation of 3 biogas-fed SOFCs to provide the WWTP with the co-generated heat and power and reduce its dependency on fossil energy. Overall, the sub-MW CHP system will include 3 biogas-fed SOFC stack modules, a supplementary boiler, a biogas holder and a connection for electricity and natural gas between the system and the grid. The dynamic behaviour of the SOFC-based CHP has been modelled through minimum up- and down-time, ramp limits, constraints for energy consumption during start up/shut down, as detailed later in section 5.

Although SOFCs are the prime mover studied in this work, in order to provide a comprehensive assessment of their level of technological readiness, the appraisal of state-of-the-art technologies, such as MGT and ICE, is also proposed using the same methodology based on a cost optimal unit commitment model for CHP systems. Figure 2 summarizes the main CHP plant configurations analysed in this work. For this reason, any engine type will be generally referred as CHP unit or generator when necessary and, in particular, in the mathematical formulation.

The problem can be stated as follows. Given:

- the techno-economic characterisation of each single CHP unit in terms of
  - capacity
  - piecewise profile for electrical and heat efficiency
  - capital, maintenance and stack replacement costs
  - ramp rates
  - minimum up- and down-times
- the techno-economic characterisation of the clean-up system (i.e. capital and maintenance costs)
- the supplementary integrated boiler capacity
- the supplementary boiler efficiency profile, which is assumed constant despite variations of fuel inlet flow and quality (i.e. natural gas and biogas mixtures)
- the minimum and maximum biogas holder levels
- the annual electricity demand profile of the WWTP on an hourly basis
- the annual thermal demand profile of the WWTP on an hourly basis

the model minimises the total annual costs of the energy provision system which fulfils the WWTP thermal and electrical demand and defines its optimal operating strategy hour-by-hour. As such, the decision variables are

- the dispatch state of each CHP unit on an hourly basis (which defines number and occurrence of shut-downs and start-ups in a year)
- the electrical and thermal output of each CHP unit on an hourly basis
- the boiler thermal output on an hourly basis
- the electricity and natural gas bought from the grid and associated $CO_2$ emissions on an hourly basis
- the biogas flow used in the CHP units on an hourly basis
- the biogas holder levels on an hourly basis
- the amount of biogas unexploited (i.e. flared) on an hourly basis

Section 1 reports the symbols of the decision variables used in the mathematical formulation.
The anaerobic digester dynamic behaviour has not been modelled, but the hourly biogas flow rate

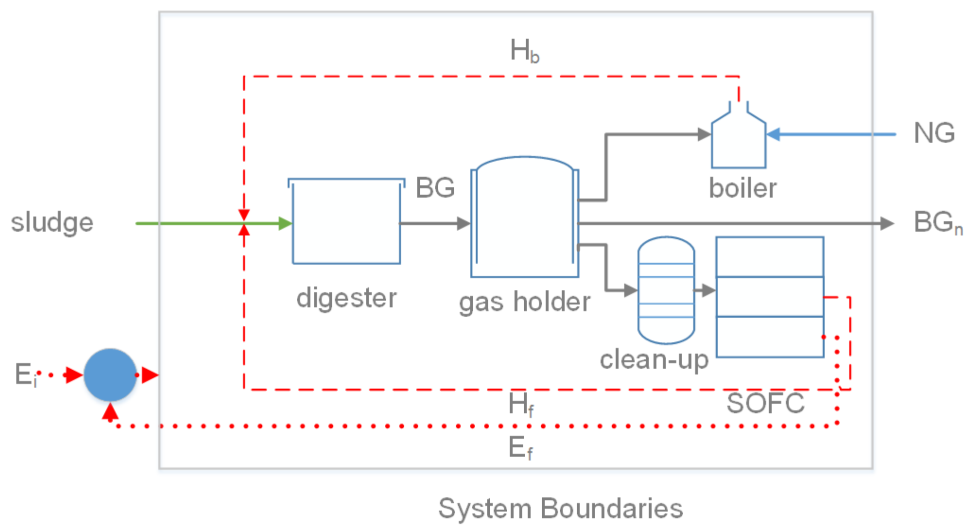


Figure 1: System boundaries of the study and relevant energy flows. BG indicates the biogas produced from anaerobic digestion, $BG_n$ is the biogas which remains unexploited, $E_f$ is the electric energy generated from the SOFC, $E_i$ is the electricity bought from the grid, $H_b$ is the thermal energy generated from the boiler, $H_f$ is the thermal energy obtained from heat recovery of the SOFC system.

of a real WWTP is an input to the optimisation.
The SMAT Collegno WWTP (SMAT, 2016), located in the Turin area, currently uses biogas to supply a boiler and partially provide the heat required by the plant. According to the retrofitting project, the same biogas after clean-up will be also used to feed the SOFC modules which will work as a sub-MW CHP unit, supplying both heat and power to the system. The WWTP has a capacity

corresponding to 180,000 EP. The average electrical and thermal loads are around 650 and 341 kWh in a year. Thermal energy requirement is mainly due to maintaining the digester temperature generally above the 40 °C in order to allow the biological process to succeed.
The biogas composition might vary in a year due to change in the quality and quantity of the waste water treated at the plant. The techno-economic appraisal is here performed considering a biogas with a lower heating value of 21,501 kJ/m$^3$. A constant chemical composition of biogas was assumed throughout the year, as reported in Table 1, which meets the quality specifications for supplying an SOFC system.

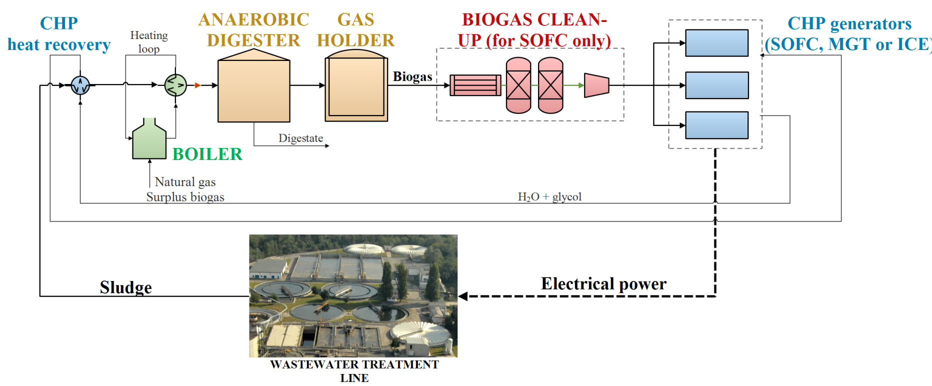


Figure 2: Integrated WWTP CHP plant configurations analysed in this work.

Table 1: Biogas chemical composition on a molar basis assumed in the technoeconomic appraisal

| Compound | Molar fraction |
|---|---|
| $CH_4$ | 0.65 |
| CO | 0 |
| $CO_2$ | 0.331 |
| $H_2$ | 0 |
| $H_2O$ | 0.01 |
| $O_2$ | 0.002 |
| $N_2$ | 0.007 |

### *4.1. Clean-up system overview*

The biogas clean-up unit is required to assure a deep purification of the raw biogas from contaminants such as sulfur and organic silicon compounds. In the WWTP retrofitting plan, the clean-up unit comprises of six adsorption vessels, filled with commercial impregnated activated carbons for siloxanes and sulfur ($H_2S$) removal (see Figure 3). The last two reactors should act as scavengers for the fine purification of already treated biogas and they would not be necessary with a biogas at low concentrations of contaminants. Prior to the adsorption stage, there is a biogas recovery system to direct biogas from the gas holder to the fuel cell island. The biogas recovery system comprises of a chiller (to avoid condensation along the pipeline connecting the gas holder to the clean-up and fuel cell island) followed by a blower (to overcome the pressure losses over the pipeline and the adsorption beds).

The clean-up unit was designed and sized for a 6-month operation of each pair of the first 4 reactors after monitoring for one-year the raw macro and micro-composition of the raw sewage biogas; the overall system cost matches are those in Table A.2. $H_2S$ and siloxanes (mainly in the form of D4 and D5) have been detected in the raw biogas that are also known to be detrimental for the durable operation of the SOFC system ((Lanzini et al., 2017), (Papadias et al., 2012), (Madi et al., 2015)). (Lanzini et al., 2017) and (Papadias et al., 2012) have extensively analyzed and reviewed techniques for the removal of biogas contaminants to meet the high-temperature fuel cell requirements. When the concentration of contaminants is low (tens of ppm) (i.e. the average yearly concentration of $H_2S$ and equivalent D4-siloxane measured respectively about 20 and 1 ppm in the WWTP used as a reference for this work) adsorption systems based on activated carbons (either impregnated or mixed with metal oxides) have been pointed out as the most viable solution for biogas ultra-purification.

## 5. Mathematical formulation

The MILP model here described extends the optimal unit commitment problem developed by (Nowak & Römisch, 2000) and the economic appraisal proposed by (Hawkes et al., 2009) to optimise the operating strategy of a sub-MW co-generation system which included $n$ CHP generators of the same type integrated to the WWTP. Specifically, the modelling framework proposed was used to study the optimal dispatch and costs of 3 CHP units and was sequentially applied to SOFCs, MGTs and ICEs.

In the following, the objective function will be first presented, then the equations concerning the fulfilment of energy balances, the CHP unit specific constraints and the system constraints will be outlined. The full list of symbols is reported in section 1.

### *5.1. Objective function*

The model minimises the CHP system total annual costs, $TC$, which consist of the sum of fixed costs and variable operating costs over the total number of hours $t$ in a year:

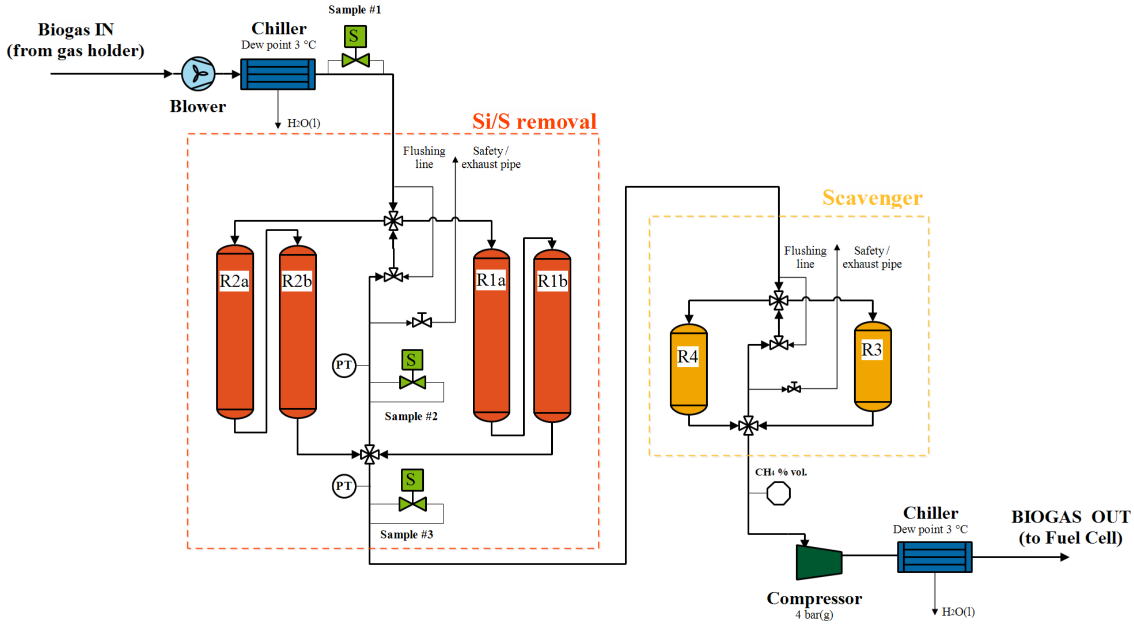


Figure 3: Clean-up section in the DEMOSOFC plant. Each reactor is filled with activated carbons which is more selective to remove either Si or S. Reactors R1a and R2a removes siloxane compounds, while R2a and R2b are selective for $H_2S$ removal. The scavenger section (R3 and R4) provides a further polishing of the cleaned biogas to remove residual sulfur and organic compounds.

- fixed costs include maintenance costs for the CHP units and clean-up systems which are proportional to the CHP nameplate capacity ($n \cdot Pnom$) and depend on the unit maintenance and clean-up costs, $UMC$ and $UOC$ respectively. The supplementary boiler maintenance costs are also accounted for ($UMCb \cdot BCap$);

- variable operating costs account for the costs related to the fuel sent to the supplementary thermal unit and the CHP unit ($NGD_t$), electricity bought from the grid ($Ei_t$) as well as the carbon price *cp* associated to the energy mix carbon intensity ($ge$, $ee$)

$$TC = \sum_t (NGD_t \cdot (gp_t + cp \cdot ge) + Ei_t \cdot (ep_t + cp \cdot ee)) \quad (1)$$

$$+ (UMC + UOC) \cdot n \cdot Pnom + UMCb \cdot BCap \quad (2)$$

*5.2. Energy balances*

The sub-MW CHP system has to obey the biogas balance in Eq. (3) which reflects the energy flows in Figure 1. The flow of biogas from the anaerobic digester $BGi_t$ at time $t$, is split among these possible destinations:

- fuelling the boiler ($BGb_t$),

- fuelling all the CHP units $f$ during their regular operation at a selected regime $r$ ($BGCHP_t$), or during start ($BGS_{t,f}$) and stop events ($BGD_{t,f}$) [1]
- being flared ($BGn_t$)
- being stored in the biogas holder ($GH_t$)

$$BGi_t - BGb_t - BGCHP_t - \sum_f (BGS_{t,f} + BGD_{t,f}) - BGn_t = GH_{t+1} - GH_t, \quad t \leq t8759 \tag{3}$$

Eq. (4) concerns the system thermal balance. Accordingly, the on-site heat demand ($DTL_t$) is met by a combination of useful heat from the committed CHP units $f$ ($CHPT_t$), the supplementary boiler where both natural gas ($NGb_t$) and biogas ($BGb_t$) can be burned. The supplementary boiler is assumed to operate at the same efficiency $\eta^b$ with both the fuels.

$$(NGb_t + BGb_t) \cdot \eta^b + CHPT_t = DTL_t \tag{4}$$

Finally, Eq. (5) guarantees the electricity balance of the system. The on-site electricity demand is made up of:

- the WWTP electrical demand $Ed_t$,
- the clean-up utility $u$ electrical demand, proportional to the biogas $\frac{Xb_{t,r,f}}{\epsilon_r^{fb}}$ and natural gas $\frac{Xn_{t,r,f}}{\epsilon_r^{fn}}$ used in the generators according to the unit energy consumption $UEC_u$ of utility $u$
- the electricity absorbed during start-ups $PSS_{t,f}$ and shut-downs $PSD_{t,f}$ of each cell $f$

As stated in Eq. (5), at every hour $t$, the on-site electrical demand is met by a combination of power generated from the CHP units $CHPE_t$ and electricity from the grid $Ei_t$.

$$Ei_t + CHPE_t = Ed_t + \sum_{u,f,r} UEC_u \cdot \left(\frac{Xb_{t,r,f}}{\epsilon_r^{fb}} + \frac{Xn_{t,r,f}}{\epsilon_r^{fn}}\right) + \sum_f (PSS_{t,f} + PSD_{t,f}) \tag{5}$$

*5.3. CHP constraints*

*5.3.1. Start-up and shut-down events*

Eq. (6) and Eq. (7) define the minimum up- and down-time constraints for the CHP units. The formulation is based on the approach by (Nowak & Römisch, 2000) and constrains the value of the binary variable $\upsilon_{t,f}$ which defines the commitment state of each CHP unit $f$ at time $t$.

$$\upsilon_{t-1,f} - \upsilon_{t,f} \geq -\upsilon_{\tau,f}, \quad \forall \tau \in upt_t \subset T, t \geq t2 \tag{6}$$

$$\upsilon_{t-1,f} - \upsilon_{t,f} \leq 1 - \upsilon_{\tau,f}, \quad \forall \tau \in dot_t \subset T, t \geq t2 \tag{7}$$

[1] As detailed in the following, the electrical and thermal performance of the CHP units, SOFCs, MGTs and ICEs, have been modelled using two regimes: nominal conditions and partial load operations.

These constraints are not as relevant for MGTs and ICEs, as they are for SOFCs. In fact, they prevent the SOFC thermal cycling, a major cause of fuel cell degradation. As such, once committed, the cell is forced to remain switched on for a minimum number of hours equal to the minimum up-time (Eq. (6)). In a similar fashion, once the cell is switched off, it is constrained to remain at that stage at least for a number of hours equal to the minimum down-time (Eq. (7)).

Power ($PSU_{t,f}$, $PSD_{t,f}$) and biogas ($BGS_{t,f}$, $BGD_{t,f}$) respectively consumed during start and stop processes are calculated distributing the average rate of electricity ($PSUabs$, $PSDabs$) and biogas ($BGSabs$, $BGDabs$) absorbed over the entire duration of the start (Eq. (8) and Eq. (10)) and stop (Eq. (9) and Eq. (11)) process. The energy consumed was used to then determine the costs associated with the start/stop processes of the generator.

$$PSU_{t,f} \geq PSUabs \cdot (\upsilon_{t,f} - \upsilon_{t-tup,f}), \quad \forall t \in T : t \geq (tup + 1) \tag{8}$$

$$PSD_{t,f} \geq PSDabs \cdot (1 - \upsilon_{t,f}) \tag{9}$$

$$BGS_{t,f} \geq BGSabs \cdot (\upsilon_{t,f} - \upsilon_{t-tup,f}), \quad \forall t \in T : t \geq (tup + 1) \tag{10}$$

$$BGD_{t,f} \geq BGDabs \cdot (1 - \upsilon_{t,f}) \tag{11}$$

If the generator $f$ state is on, it can be tuned to work at a specific operating regime which makes minimum the total system cost. The logic condition in Eq. (12) links the the generator state of commitment ($\upsilon_{t,f}$) with the binary variable for the CHP unit regime ($\chi_{t,r,f}$). Accordingly, when the generator is off, all the $\chi_{t,r,f}$ equal zero; vice versa, when the generator is on, only one operating regime can be selected.

$$\sum_{r} \chi_{t,r,f} = \upsilon_{t,f} \tag{12}$$

*5.3.2. Thermal and electrical output*

The use of natural gas $NGD_t$ inside the system, as given by Eq. 13 occurs in the boiler $NGb_t$ and in generators such as MGTs and ICEs. The second contribution is proportional to the electrical output of each generator $f$ operating at regime $r$ using natural gas $Xn_{t,r,f}$ according to the corresponding electrical efficiency $\epsilon_r^{fb}$. While natural gas can be burnt only in MGT and ICE, biogas $BGCHP_t$ can be used in all the generators ($\frac{Xb_{t,r,f}}{\epsilon_r^{fb}}$ in Eq. 14).

$$NGD_t = NGb_t + \sum_{f,r} \frac{Xn_{t,r,f}}{\epsilon_r^{fn}} \tag{13}$$

$$BGCHP_t = \sum_{f,r} \frac{Xb_{t,r,f}}{\epsilon_r^{fb}} \tag{14}$$

The thermal $CHPT_t$ and electrical $CHPE_t$ outputs from the generators are accounted for as in Eqs. 15 and 16.

$$CHPT_t = \sum_{f,r} \left( \frac{Xb_{t,r,f} \cdot \eta_r^{fb}}{\epsilon_r^{fb}} + \frac{Xn_{t,r,f} \cdot \eta_r^{fn}}{\epsilon_r^{fn}} \right) \tag{15}$$

$$CHPE_t = \sum_{f,r} (Xb_{t,r,f} + Xn_{t,r,f}) \tag{16}$$

$$\sum_{f,r} X_{t,r,f} = CHPE_t \tag{17}$$

The technical applicability of a fuel to each generator type which then constrains the CHP electrical output is defined through piecewise efficiency functions. The electricity output of a generator is limited by its nameplate capacity ($Pnom$ in Eq. (18)). The total electricity output for each regime also has to operate between a lower ($PRL_r$) and an upper bound ($PRU_r$), as stated respectively in Eq. (19) and Eq. (20). Eq. (19) also sets the presence of a minimum set-point for the CHP operation, representing a lower bound to the economic and technical feasibility region of the CHP operation.

$$\sum_{r} X_{t,r,f} \leq \upsilon_{t,f} \cdot Pnom \tag{18}$$

$$X_{t,r,f} \geq PRL_r \cdot \chi_{t,r,f} \tag{19}$$

$$X_{t,r,f} \leq PRU_r \cdot \chi_{t,r,f} \tag{20}$$

The rate at which the generator can change its electrical output level is constrained imposing a maximum ramp up rate ($r_{up}$ in Eq. (21)). Normally, MGTs and ICEs can react very quickly to rgime variations. However, rump up constraints are important for SOFCs in order to reduce mechanical stress caused by thermal gradients in the fuel cells.

$$r_{up} \geq \sum_{r} X_{t,r,f} - X_{t-1,r,f}, \quad \forall t \in T : t \geq t2 \tag{21}$$

*5.4. System constraints*

In a similar way to the nameplate capacity limit imposed to the generators in Eq. (18), physical capacity limits are modelled for all the CHP system units: Eq. (22) defines a lower ($GHL$) and an upper ($GHU$) bound to the biogas storage; Eq. (23) sets that the boiler thermal power must not exceed its capacity ($BCap$).

$$GHL \leq GH_t \leq GHU \tag{22}$$

$$BCap \geq (NGb_t + BGb_t) \cdot \eta^b \tag{23}$$

Finally, a periodic condition is set to ensure that the CHP operational strategy applies from one year to the next one until the end of the system lifetime. The periodic condition is stated with Eq.

(24) where the gas holder level at the beginning of the year has to equal the value at the end of the year.

$$GH_{'t1'} = GH_{'t8760'} \tag{24}$$

## 6. Real-world industrial case study

A techno-economic assessment was performed for the retrofit of the energy supply system of a sub-MW WWTP operating in Collegno, Italy. The heat supply to the facility currently relies on a gas boiler, while electricity is bought from the grid. The retrofit plan involves the installation of a 3-module SOFC-based CHP system fuelled with biogas. A comparative assessment of the SOFCs with the available state-of-the-art CHP technologies, such as ICEs and MGTs is also presented. Selected technical characteristics of the current energy supply system (i.e. boiler and gas holder), are reported in Table 2.

Table A.1 and Table A.2 provide the technical assumptions of the generators (e.g. lifetime, net alternating current or AC, capacity, minimum up/down time, power absorbed and biogas consumed during start-up and down-time events) as well as the cost assumptions for short, medium and long term.

In the current configuration, a gas holder operates approximately at atmospheric pressure, receives the biogas from the digester and flattens the rate fluctuations before the boiler. According to the WWTP retrofitting project, a biogas clean-up and a 3-module SOFC system will be located in an additional branch of the gas holder downstream.

Table 2: Selected techno-economic performance of boiler and gas holder, which belong to the currently installed configuration for heat supply to the WWTP; of MGT and SOFCs

| Boiler technical input | unit | value | source |
|---|---|---|---|
| Capacity | kW | 1,600 | estimated |
| Efficiency | % | 85 | estimated |
| Maintenance costs | % of CAPEX | 3 | (Pantaleo et al., 2014) |
| Gas holder technical input | unit | value | source |
| Minimum capacity | kWh | 1,791.75 | (DEMOSOFC, 2016) |
| Minimum capacity | $m^3$ | 300 | (DEMOSOFC, 2016) |
| Maximum capacity | kWh | 8,361.5 | (DEMOSOFC, 2016) |
| Maximum capacity | $m^3$ | 1,400 | (DEMOSOFC, 2016) |

Electrical and thermal efficiencies in any CHP unit vary with the stack current and, consequently with the rate of biogas used. In order to balance a more realistic description of the generator behaviour while keeping the model linear and computationally tractable, the profile of the thermal and electrical efficiencies has been modelled using a piecewise linear function having two operating regimes. One regime describes the nominal operating conditions: here the CHP exhibits the best performance and can exploit up to 100 % of the fuel rate allowed into the system. A second regime characterises the CHP partial load operations, in which up to 50 % of the maximum fuel rate is allowed into the system. Relevant features of the two regimes are summarised in Table A.1. Please note that all the CHP generators, except SOFCs, can exploit both natural gas and biogas. This certainly represents a conservative assumption for SOFCs, but is due to the current lack of industrial data.

*6.1. Description of the comparative configurations*

A framework of 5 comparative configurations was built up to help shaping the SOFC technology introduction and deployment strategies, as described in the following:

- boiler: represents the current configuration of the system which relies on heat generated by the co-fuelled (natural gas and biogas) boiler.

- MGT: considers a hypothetical WWTP retrofit based on the installation of 3-MGT units with a total net AC capacity equal to the one of the CHP system based on SOFCs (174.9 kW) as in the actual WWTP retrofitting plan. This technology was chosen as one of the most notable competing technologies to SOFCs. The MGT was modelled as integrated to the WWTP, thus providing it with the useful heat and the generated electricity. This configuration also includes a supplementary boiler, a biogas holder and a connection for electricity and natural gas of the system to the grid. Differently from the SOFCs, the MGTs can use both biogas and natural gas as fuels.

- ICE: as being a representative state-of-the-art technology, ICEs were chosen as an additional competing technology to SOFCs. This configuration involves the hypothetical installation of 3-ICE units with a total net AC capacity equal to the one of the CHP system based on SOFCs (174.9 kW) as in the actual WWTP retrofitting plan. This configuration also includes a supplementary boiler, a biogas holder and a connection for electricity and natural gas of the system to the grid. Differently from the SOFCs, the ICEs were modelled assuming that both biogas and natural gas could be used as fuels.

- SOFC: considers the integration of the sub-MW SOFC-based CHP system to the WWTP. It includes 3 biogas-fed SOFC stack modules having a total net AC capacity of 174.9 kW, a supplementary boiler, a biogas holder and a connection for electricity and natural gas of the system to the grid.

- SOFC60: considers the integration of 3 advanced SOFC units to the WWTP plant; these will exhibit an electrical efficiency of 60 %, which is a target performance easily achievable in the short-term (IEA - ETSAP, 2013). It also includes a supplementary boiler, a biogas holder and a connection for electricity and natural gas of the system to the grid. Cost assumptions are the same as in the *SOFC* configuration.

The techno-economic assumptions are in Tables A.1 and A.2.
In the following, results describe first the the optimal operating strategy of the energy generation system with the corresponding equivalent annual costs considering three scenarios:

- base (A): it involves the current WWTP thermal and electricity consumption, respectively equal to an average of 341 kWh/y and 650 kWh/y
- sludge prethickening (B): it involves the installation of a sludge thickening technology before the anaerobic digester which increases the sludge total suspended solids (TSS) from 1.91 wt. % up to 5 wt. %. The prethickener operation involves a modest increase in the electrical load (by less than 0.5 %), but a considerable reduction of the digester thermal load is obtained.
- advanced sludge prethickening (C): it includes an upgrade of the sludge WWTP handling section, introducing an advanced sludge prethickener which would rise the TSS up to 8 wt. %, with a considerable reduction of the digester thermal loads. Electrical loads would grow by less than 1 % from the base scenario.

Second, a cost appraisal of the selected system configurations will be proposed where SOFC cost projections due to technological learning will be included. The remit of the analysis will be the Italian market. Also, an assessment of the energy vector price effects will be made using the UK as a reference alternative market.
These economic inputs will apply to the Italian market case study:

- natural gas price constant throughout the year and equal to 0.06 €/kWh, which is typical for WWTP plants (DEMOSOFC, 2016)
- electricity hourly price profile was based on industrial prices for WWTPs in 2016 as provided by SMAT (DEMOSOFC, 2016)

In the UK-based case study, energy prices were updated using the country-specific costs for natural gas and electricity, as in (DECC, 2016).

The $CO_2$ emissions of the WWTP were estimated using the carbon intensity of the energy imported by the system, according to the following assumptions:

- natural gas emission factor, 0.202 kg$CO_2$ per kWh (IPCC, 2006)
- electricity emission factor, 0.468 kg$CO_2$ per kWh (URS Corporation, 2003)

## 7. Results and discussion

The model has been implemented using the GAMS® software and solved with the CPLEX solver. A typical optimisation run for a 3-module SOFC involves about half a million variables and solves in a few minutes. The optimal operational strategies of the key five plant configurations and the three scenarios (i.e. base, sludge prethickening, advanced sludge prethickening) as outlined in section 6 were modelled using the optmisation modelling framework.

### *7.1. Optimal operational strategies in the modelled scenarios*

The optimal operating strategy which corresponds to the minimum total system cost defines, for every hour of operation, how the biogas available could be optimally distributed among storage, CHP and boiler, as well as the amount of natural gas and electricity to import from the grid. For all the CHP configurations, the optimal dispatch involves a full-year operation with no stop events. This is particular important for SOFCs, where frequent start and stop events might provoke damages to the cell. Table 3 reports the equivalent annual cost (EAC) as well as the contributions in each configuration and in every scenario of these costs:

- the initial capital investment ($CAPEX$) due to the purchase of a novel CHP system
- the cost of future replacement (*Replacement*) of parts of the equipment engines (only for SOFCs)
- fixed operating and maintenance ($O\&M$) costs due to the ordinary maintenance of each unit $f$ of the energy supply system
- biogas clean-up system maintenance ($Clean - up$) only for SOFCs
- running operating costs due to the energy imported into the system in terms of natural gas and electricity
- carbon costs applied to $CO_2$ emissions.

The payments spread over multiple years are annualised in the $EAC$; as such, both the $CAPEX$ and the *Replacement* are included as overnight investments at a 2.5 % interest rate spanning 20 and 15 years respectively.

Please note that the results are initially presented in a carbon neutral policy scenario, where the carbon price is set to 0.

As the results show, the CHP configurations would represent an advantageous option compared to the current WWTP layout based on the use of a boiler as a means for biogas valorization. The least expensive configuration, which uses ICEs as an energy supply system (scenario A), gives a 7.8 % reduction on the EAC compared to the boiler itself. Interestingly, while current SOFCs would be 1.5 % more expensive than the boiler, if advanced performance are assumed for SOFC electricity generation (SOFC60), the EAC would be 0.6 % lower.

From the WWTP perspective, the introduction of more efficient sludge prethickening technologies (scenario B and C) would improve the overall economics. As the sludge TSS increases, the adoption of more efficient engines in terms of electrical efficiency (such as SOFCs and SOFC60s) would become an interesting business option producing up to 2 % savings compared to the boiler EAC. In this regards, it is apparent that SOFCs can relieve the WWTP running operating costs due to fuel consumption, but capital and fixed costs are higher compared to alternative technologies. Overall, capital costs still represent a barrier to commercialisation as important as the need for replacing the stack.

The CHP configurations have been compared in terms of the techno-economic performance of the power plants to generate using levelised costs (LCOE) as well as in terms of their cost performance within the WWTP adopting a system perspective (sLCOE), defined as follows:

$$LCOE = \frac{TC - Ei_t \cdot (ep_t + cp \cdot ee) + oCAPEX + oRC}{\sum_t CHPE_t} \tag{25}$$

$$sLCOE = \frac{TC + oCAPEX + oRC}{\sum_t CHPE_t} \tag{26}$$

$$oCAPEX = UCC \cdot n \cdot Pnom \cdot af \tag{27}$$

$$oRC = URC \cdot n \cdot Pnom \cdot af \tag{28}$$

$$af = \frac{i + (1+i)^{ND}}{(1+i)^{ND} - 1} \tag{29}$$

The LCOE is evaluated adding to the natural gas costs ($TC - Ei_t \cdot (ep_t + cp \cdot ee)$), the contribution of the annualised capital costs (i.e. the overnight CAPEX, $oCAPEX$) and the annualised replacement costs (i.e. the overnight replacement costs, $oRC$). $oCAPEX$ and $oRC$ are proportional to the installed capacity of the energy provision system ($n \cdot Pnom$[2]), to the unit cost (i.e. the unit capital and replacement costs, $UCC$ and $URC$ respectively) and to the annualisation factor ($af$). The

[2] $n$ equals 3 in our case study as three power generation units are assumed to be installed in the WWTP retrofitting plan.

annualisation factor $af$ depends on the interest rate ($i$, equal to 2.5 %) and the depreciation time ($ND$) typical of the selected investment.

Differently from the LCOE, the sLCOE includes the total running costs of the system ($TC$). This means that it includes the whole energy (electrical and thermal) expenditure of the WWTP, i.e., both the operating costs for electricity and NG imported from the grid are included (electricity and NG are indeed purchased from the grid whenever the internal CHP production is not sufficient to cover the WWTP loads).

In general, while the calculated sLCOE values cannot be compared with the electricity price from the grid, they are useful for a comparative assessment on the techno-economic performance of the proposed plant configurations.

Comparing the 5 configurations of the energy supply system, results show that:

- In scenario A, electricity generation costs (embodied in the LCOE) are the lowest when high thermal efficiency engines such as ICEs are installed. Also, either ICEs or MGTs, which display a lower LCOE than the average electricity price (0.157 €/kWh), would be more convenient than importing electricity from the grid. Compared to MGTs, SOFCs suffer from a high share of fixed costs due to both capital and replacement costs.

- In scenario B, where prethickening technologies are introduced, the MGT is the most convenient option, but the LCOE for the configuration SOFC60 becomes comparable with the ICE one.

- In scenario C, where advanced prethickening technologies are used, the situation changes dramatically, showing more than 30 % reduction on the LCOE for SOFCs compared to the MGT configuration and more than 50 % reduction compared to the ICE one.

Interestingly, if a system perspective is considered using the sLCOE, the configuration SOFC60 appears more profitable in all the scenarios due to the highest electricity output.

Table 3: Equivalent annual costs ($EAC$, €/y)), electricity costs ($Electricity$, €/y), natural gas costs ($NG$, €/y), capital investment ($CAPEX$, €), replacement (€/replacement), maintenance costs (€/y), clean-up costs (€/y) for boiler, MGT, ICE, SOFC and SOFC60 in the base (A), sludge prethickening (B) and advanced prethickening (C) scenarios.

| Configuration | Electricity | NG | CAPEX | Replacement | O&M | Clean-up | EAC |
|---|---|---|---|---|---|---|---|
| A | | | | | | | |
| Boiler | 877,892 | 7,216 | - | - | 11,200 | - | 896,308 |
| MGT | 670,896 | 144,817 | 493,218 | - | 32,888 | - | 880,238 |
| ICE | 691,495 | 65,162 | 454,215 | - | 40,059 | - | 825,852 |
| SOFC | 656,445 | 95,447 | 1,612,578 | 213,903 | 23,793 | 13,292 | 909,696 |
| SOFC60 | 652,111 | 81,137 | 1,612,578 | 213,903 | 23,793 | 13,292 | 891,051 |
| B | | | | | | | |
| Boiler | 881,909 | - | - | - | 11,200 | - | 893,109 |
| MGT | 745,011 | 7,387 | 493,218 | - | 32,888 | - | 816,925 |
| ICE | 778,094 | - | 454,215 | - | 40,059 | - | 847,289 |
| SOFC | 660,486 | 12,720 | 1,612,578 | 213,903 | 23,793 | 13,292 | 831,009 |
| SOFC60 | 656,158 | 8,471 | 1,612,578 | 213,903 | 23,793 | 13,292 | 822,433 |
| C | | | | | | | |
| Boiler | 885,280 | - | - | - | 11,200 | - | 896,480 |
| MGT | 778,468 | - | 493,218 | - | 32,888 | - | 842,994 |
| ICE | 804,483 | - | 454,215 | - | 40,059 | - | 873,678 |
| SOFC | 663,888 | 5,405 | 1,612,578 | 213,903 | 23,793 | 13,292 | 739,345 |
| SOFC60 | 659,590 | 2,901 | 1,612,578 | 213,903 | 23,793 | 13,292 | 732,544 |

Table 4: LCOE and sLCOE (€/kWh) for MGT, ICE, SOFC and SOFC60 in the base (A), sludge prethickening (B) and advanced sludge prethickening scenario (C).

| Configuration | LCOE (€/kWh) | sLCOE (€/kWh) |
|---|---|---|
| A | | |
| Boiler | n.a. | n.a. |
| MGT | 0.146 | 0.612 |
| ICE | 0.104 | 0.641 |
| SOFC | 0.173 | 0.623 |
| SOFC60 | 0.161 | 0.600 |
| B | | |
| Boiler | n.a. | n.a. |
| MGT | 0.076 | 0.859 |
| ICE | 0.097 | 1.182 |
| SOFC | 0.117 | 0.569 |
| SOFC60 | 0.112 | 0.554 |
| C | | |
| Boiler | n.a. | n.a. |
| MGT | 0.087 | 1.136 |
| ICE | 0.124 | 1.565 |
| SOFC | 0.059 | 0.514 |
| SOFC60 | 0.057 | 0.501 |

The CHP output for each configuration in the 3 scenarios, is displayed in Table 5 in terms of electricity and useful heat generated at the CHP systems. The values are reported alongside the electrical and thermal loads. Results from Table 5 highlight that the best electrical performance of SOFC60 allows 26 % of electrical ratio in scenario A (25 % of thermal ratio). MGTs and ICEs follow with, respectively, an electrical ratio of 25 % and 23 %. It is to note that MGT and ICE take advantage of the possibility of natural gas integration (see also Figure 4). This also allows them to cover a high share of the load (77 % and 91 %, respectively) even in scenario A. Moving from scenario A, towards C where the thermal loads are reduced, MGT and ICE are capable to cover the full load. At the same time, though, the electricity import increases as the engines operated most often at the highest thermal efficiency in partial load conditions. Moving from scenario A to B and C, SOFCs also improve the electrical ratio up to 49 % and 63 %, respectively, with a slight worsening of the electrical ratio (25 %).

It is interesting to note that all the CHP configurations in the base scenario do need to import natural gas to fulfil the plant thermal needs (see Figure 4). Since the ICE displays the best thermal performance among the co-generation alternatives, it also shows by far the lowest reliance on imported natural gas. On the contrary, the MGT configuration shows the highest reliance on imported gas for co-generation. In the SOFC and SOFC60 configurations, biogas is used preferably for co-

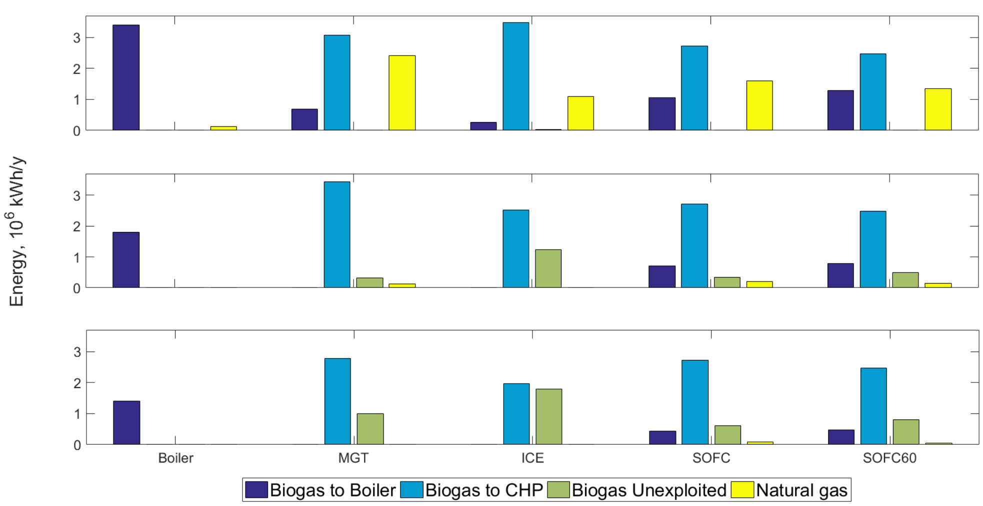


Figure 4: Share of inlet carriers to the system: biogas flow sent to the boiler, biogas sent to the CHP system, biogas unexploited and natural gas for the configurations studied (boiler only, MGT, ICE, SOFC and SOFC60) in scenario A (top), B (middle) and C (bottom).

generation in the cell rather than for pure combustion in the boiler. Natural gas is only fed to the boiler. Cell performance is affected by the scarce availability of biogas during summer (around 6,000 hours of operation), as shown by the hour-by-hour profiles of biogas in Appendix B. Hourly heat

Table 5: Optimal commitment strategy: electricity demand (Electrical load, kWh/y), electricity produced from the CHP (Electricity output, kWh/y), heat demand (Thermal load, kWh/y) and thermal energy produced from the CHP system (Thermal output, kWh/y), for a year of operation.

| Configuration | Electrical load | Electricity output | Thermal load | Thermal output |
|---|---|---|---|---|
| A | | | | |
| Boiler | 5,644,464 | - | 2,987,595 | - |
| MGT | 5,714,314 | 1,437,758 | 2,987,595 | 2,303,100 |
| ICE | 5,723,589 | 1,287,530 | 2,987,595 | 2,741,223 |
| SOFC | 5,706,115 | 1,461,157 | 2,987,595 | 742,529 |
| SOFC60 | 5,700,672 | 1,485,665 | 2,987,595 | 742,832 |
| B | | | | |
| Boiler | 5,669,974 | - | 1,526,954 | - |
| MGT | 5,747,861 | 950,579 | 1,526,954 | 1,522,703 |
| ICE | 5,727,367 | 717,035 | 1,526,954 | 1,526,607 |
| SOFC | 5,731,619 | 1,461,006 | 1,526,954 | 742,452 |
| SOFC60 | 5,726,175 | 1,485,483 | 1,526,954 | 742,741 |
| C | | | | |
| Boiler | 5,691,380 | - | 1,188,383 | - |
| MGT | 5,754,326 | 741,765 | 1,188,383 | 1,188,211 |
| ICE | 5,736,056 | 558,158 | 1,188,383 | 1,188,350 |
| SOFC | 5,753,019 | 1,460,879 | 1,188,383 | 742,387 |
| SOFC60 | 5,747,574 | 1,485,316 | 1,188,383 | 742,658 |

and electricity generations for the SOFC configuration are also reported for reference in Appendix B.

In terms of environmental performance, SOFC60 allows to reduce the total emissions to 2,245 t/y, with a 16 % decrease from the boiler configuration and 3 % decrease from the ICE configuration.

### *7.2. Technological learning*

Technological learning pathways have been modelled projecting future cost reductions in the investment in the stacks as well as in the replacement of the modules, according to the trends displayed in (Ammermann et al., 2015), boosted by increase in the manufacturing volume. In the short term (corresponding to a cumulated manufacturing volume of 1,000 units), overnight CAPEX as well as the stack replacement cost would decrease by more than 50 % compared to the current state of SOFC development, which corresponds instead to only 100 units manufactured units. In the long-term (10,000 manufactured units), cost reductions would reach 75 % for the capital expenditure and 61 % for the stack replacement. The clean-up system investment as well as the maintenance costs are assumed to follow the same trajectory (see Table A.2).

If these cost reductions would materialize, the SOFC technology could become advantageous without specific subsidies, as shown by the EAC of the plant configurations in Figure 5. Obviously, the proven feasibility of SOFC installations at a demonstration scale is necessary to boost larger manufacturing volumes of SOFC, thus promoting the technological learning.

### *7.3. SOFC integration in the UK market*

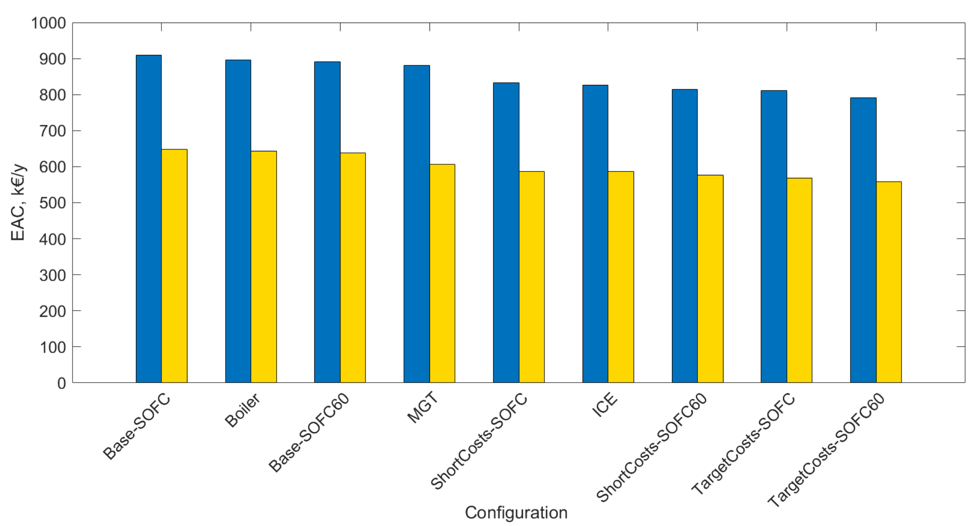


Figure 5: EAC in the Italian (in blue) and UK (in yellow) markets for the CHP configurations studied (MGT, ICE, SOFC and SOFC60) including short- and target-cost trajectories for SOFC and SOFC60.

Figure 5 compares the EAC of the energy provision system according to the selected configurations in the Italian and the UK market. It is noticeable that all the configurations realize a cheaper business case than the Italian equivalent. There is no remarkable difference in the operating strategies of the selected configurations, but the outcome is exclusively driven by the lower energy costs of the UK market: 11 % and 40 % of reduction on electricity and natural gas prices.[3]

### *7.4. Carbon price*

A carbon price policy would favour SOFC up to a certain extent. In fact, at a carbon price of 25 €/t of $CO_2$, results show that the SOFC EAC (967,000 €/y) would align with the boiler one (963,000 €/y), while the SOFC60 would be cost comparable with the MGT (with an EAC equal to 947,000 and 943,000 €/y, respectively). It is important to mention that the ICE generally turns out to be the cheapest technological solution (884,000 €/y), because of the remarkably low import of natural gas which drives the emissions down.

[3] An exchange rate from GBP to € equal to 1.12 was used as per currency quotations in July 2017.

## 8. Concluding remarks

This work studies the technical and economic feasibility of SOFCs in WWTPs applying a cost optimal dispatch mathematical model to the energy provision system retrofit of a real plant operating near Turin (Collegno).

The mathematical MILP modelling framework used for the minimum cost unit commitment of the WWTP retrofitted with a sub-MW SOFC CHP system was presented. Constraints were also included to represent SOFC dynamics, such as minimum up-time, ramp limits, and start-up/shut-down costs. A techno-economic appraisal was built onto the optimal operating strategy for the system. A series of potential plant configurations were studied to build up a framework for comparative performance assessment of SOFCs against state-of-the-art technologies. The configurations included: the current system configuration using a boiler, a hypothetical 3-module micro gas turbine CHP system, a hypothetical 3-module internal combustion engine CHP system, a 3-module SOFC-based CHP system, a 3-module SOFC-based CHP system exhibiting 60 % of electrical efficiency. Three scenarios were also studied from the WWTP layout, involving sludge prethickening (5 % TSS) and advanced sludge prethickening technologies (8 % TSS). The techno-economic analysis was also extended to include alternative markets (such as the UK case) and alternative policies (such as the inclusion of a carbon price). The modelled scenarios were assessed in terms of equivalent annual costs and levelised cost of electricity.

From the end-users prospective, results show first that there is a general interest for WWTPs with anaerobic digesters to adopt co-generation rather than just burn the excess biogas. In particular, the adoption of a biogas-fuelled SOFC-based CHP in the studied wastewater treatment plant allows a thermal self-sufficiency rate of 25 %, while the electrical self-sufficiency rate is 26 %. At the same time, running operating costs as well as the emissions of methane to the atmosphere are reduced. Second, if technologies to reduce the overall thermal needs in WWTPs are exploited, the selection of an engine operating at high electrical efficiency, such as SOFCs, becomes even more interesting. The introduction of sludge thickening technologies achieving up to 8 % of total suspended solids, make SOFCs exhibit up to 50 % of LCOE reduction compared to alternative available technologies. Third, the selection of medium scale SOFCs would represent an interesting option for WWTPs to leverage risks associated to the high capital costs of these modules.

From the manufacturers prospective, it is apparent that fixed costs are the major barrier to the technology deployment. Current stage of development of this technology involves high investment costs and frequent replacements of the stack, which still represents a considerable share of the cost of the module. In the near term, manufacturing of the modules should aim to increase the lifetime of the stacks, thus reducing the number of replacements. Also, the cells should be capable of handling fuel gas mixtures, such as biogas and methane, in order to be less constrained by the seasonal availability of biogas. Finally, electrical yields should reach 60 % as a general standard in order to have comparable costs to the best available technologies, thus leading to economy of scale effects and fostering further cost reduction.

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## Appendix A

*Input data for modelling the CHP generator units*

Table A.1: Techno-economic assumptions of the CHP system. Sources: (Ken Darrow & Hampson, 2015) for ICE, (General Electric, 2017) for MGT, (DEMOSOFC, 2016) for SOFCs. Technical characteristics for SOFC60 have been assumed considering the technology potential. Please note that efficiencies for MGT and ICE are applied equally to either biogas and natural gas; efficiencies for SOFC and SOFC60 are applicable to biogas only.

| Technical input | unit | MGT | ICE | SOFC | SOFC60 |
|---|---|---|---|---|---|
| Module lifetime | years | 20 | 20 | 20 | 20 |
| Net AC Electric Capacity | kW | 58.3 | 58.3 | 58.3 | 58.3 |
| Number of modules installed | number | 3 | 3 | 3 | 3 |
| Minimum up-time | hours | 1 | 1 | 24 | 24 |
| Minimum down-time | hours | 1 | 1 | 24 | 24 |
| Maximum ramp up | kWh/h | n.a. | n.a. | 40 | 40 |
| Power for start up | kWh/h | 0 | 0 | 40 | 40 |
| Biogas for start up | kWh/h | 0 | 0 | 17.09 | 17.09 |
| Power for shut down | kWh/h | 0 | 0 | 5 | 5 |
| Biogas for shut down | kWh/h | 0 | 0 | 17.09 | 17.09 |
| **SOFC nominal condition** | **unit** | **MGT** | **ICE** | **SOFC** | **SOFC60** |
| Ratio of biogas rate over maximum | % | 50 - 10 | 50 - 10 | 50 - 10 | 50 - 10 |
| Net AC Power | kW | 29.65 – 58.3 | 29.65 – 58.3 | | |
| Thermal efficiency | % | 42.85 | 60.38 | 27.34 | 30 |
| Electrical efficiency | % | 26.75 | 28.36 | 53.8 | 60 |
| **Partial load operation** | **unit** | **MGT** | **ICE** | **SOFC** | **SOFC60** |
| Ratio of biogas rate over maximum | % | 50 - 30 | 50 - 30 | 50 - 30 | 50 - 30 |
| Net AC Power | kW | 17.49 – 29.65 | 17.49 – 29.65 | 16.6–29.65 | 16.6–29.65 |
| Thermal efficiency | % | 47.35 | 64.09 | 31.52 | 31.52 |
| Electrical efficiency | % | 22.25 | 24.65 | 41.2 | 41.2 |

Table A.2: Techno-economic characteristics of the CHP systems in the current, short-term and target scenario of technological development

| ICE cost input (Ken Darrow & Hampson, 2015) | Unit | current | short-term | target [4] |
|---|---|---|---|---|
| Unit CAPEX | €/kW | 2,597 | 2,597 | 2,597 |
| Maintenance | €/kW-y | 165 | 165 | 165 |
| Unit lifetime | years | 20 | 20 | 20 |
| **MGT cost input (General Electric, 2017)** | **Unit** | **current** | **short-term** | **target** |
| Unit CAPEX | €/kW | 2,820 | 2,820 | 2,820 |
| Maintenance | €/kW-y | 124 | 124 | 124 |
| Unit lifetime | years | 20 | 20 | 20 |
| **SOFC cost inputs (Ammermann et al., 2015)** | **Unit** | **current** | **short-term** | **target** |
| Module CAPEX | €/kW | 8,303 | 3,346 | 2,077 |
| Stack Replacement | €/kW | 1,223 | 540 | 478 |
| Maintenance | €/kW-y | 72 | 54 | 44 |
| Gas clean-up CAPEX (Argonne National Laboratory, 2014) | €/kW | 917 | 459 | 183 |
| Gas clean-up OPEX (Argonne National Laboratory, 2014) | €/kW-y | 76 | 57 | 38 |

## Appendix B

*Hourly profiles of major variables*

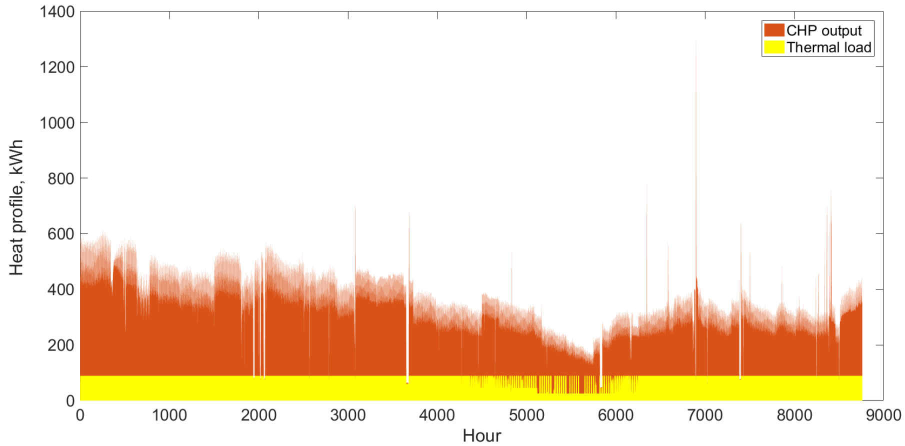


Figure B.1: Heat supply to WWTP on hourly basis: light yellow represents heat provided by the boiler; dark yellow indicates heat provided by SOFCs

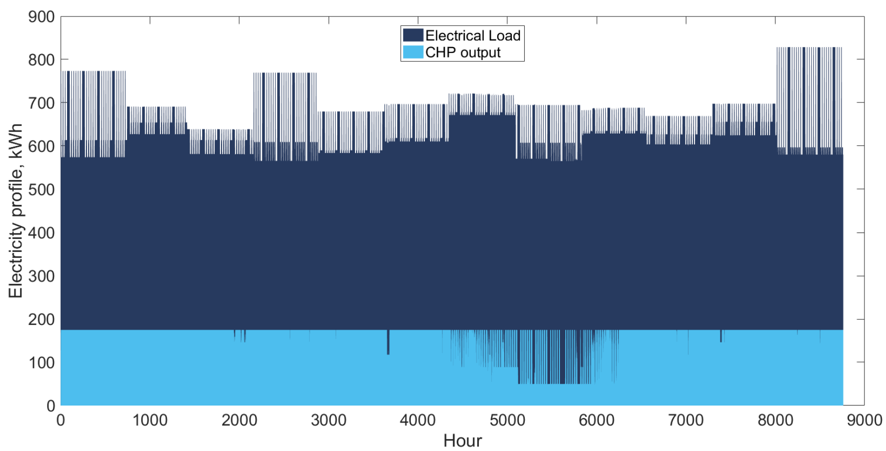


Figure B.2: Electricity supply to WWTP on hourly basis: dark blue represents electricity imported by the grid; light blue indicates electricity provided by SOFCs

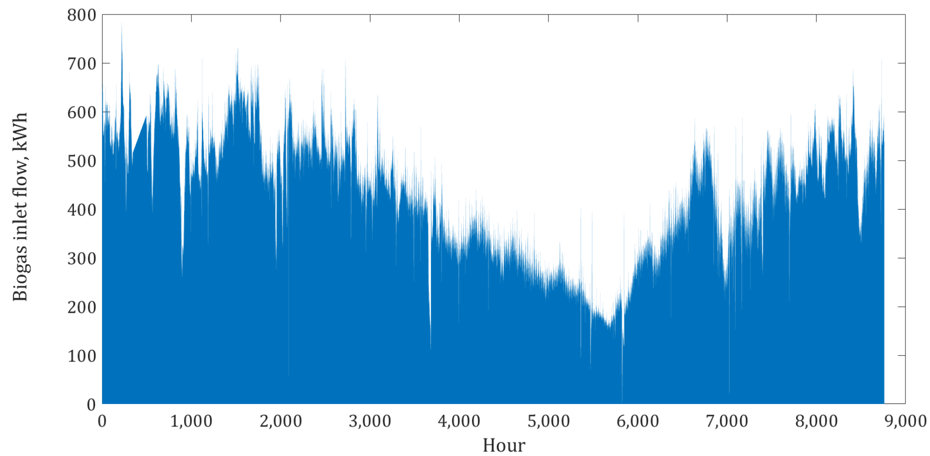


Figure B.3: Biogas flow from the digester on hourly basis (kWh) (DEMOSOFC, 2016)

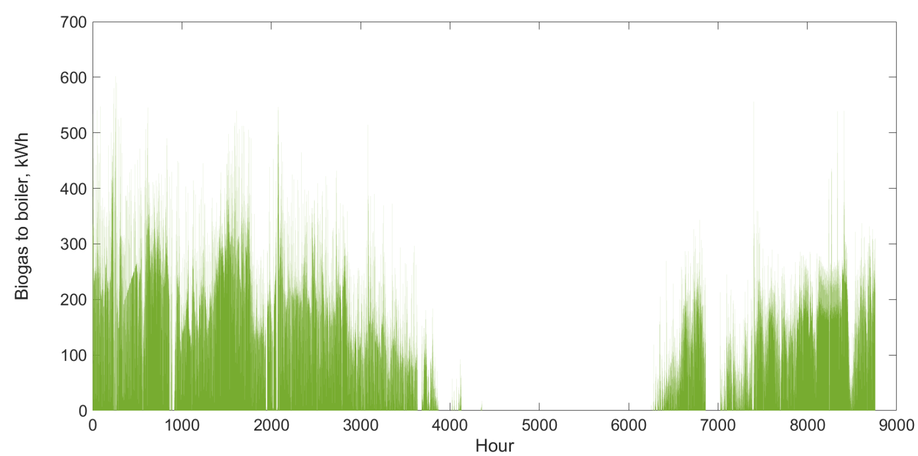


Figure B.4: Hourly profile of biogas rate to boiler (kWh)

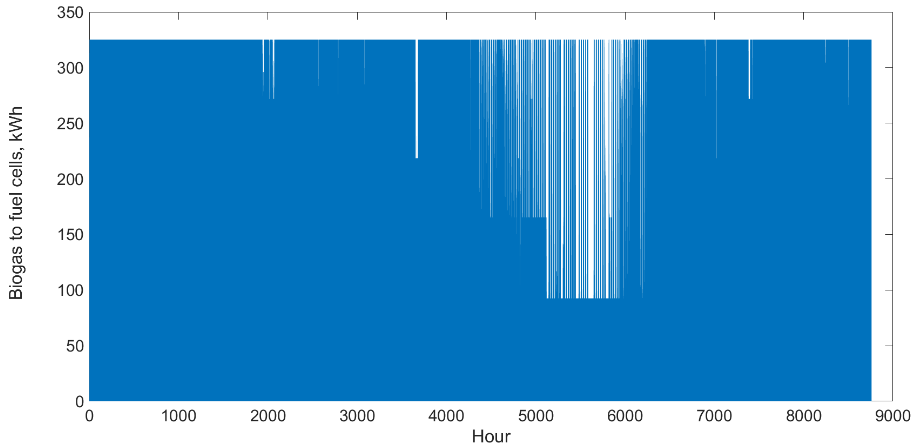


Figure B.5: Hourly profile of biogas rate to SOFCs (kWh)

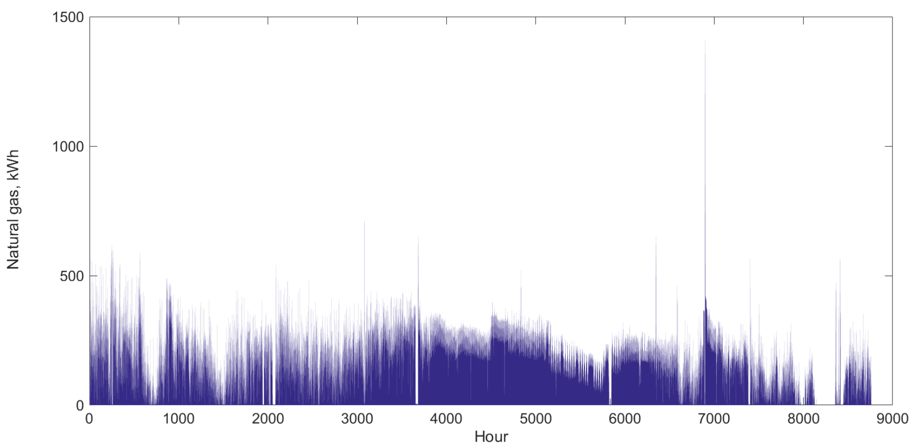


Figure B.6: Hourly profile of natural gas bought from grid (kWh)

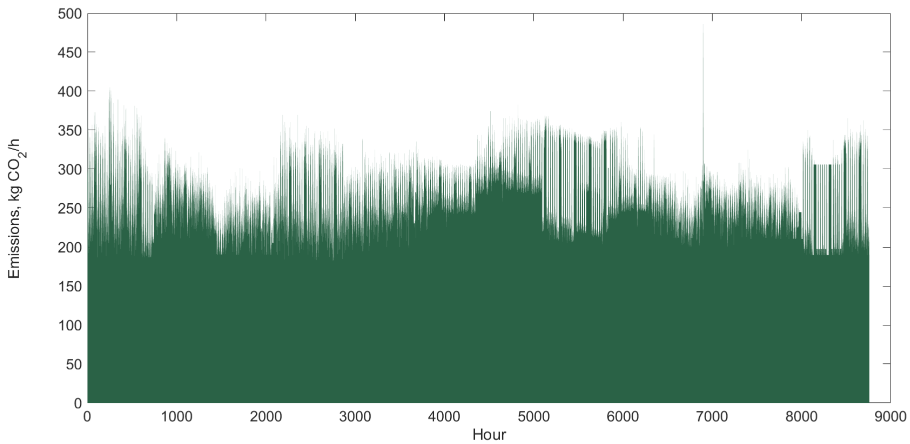


Figure B.7: Hourly profile of WWTP emissions (kg $CO_2$/h)