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# On-site cogeneration with sewage biogas via high-temperature fuel cells: Benchmarking against other options based on industrial-scale data

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ABSTRACT

The application of high-temperature fuel cells in Waste Water Treatment Plants (WWTPs) combines a high-efficiency electricity generation technology and a renewable fuel, thus simultaneously mitigating greenhouse gas emissions and resource depletion. This study investigates the current applicability and limitations of biogas-powered Molten Carbonate Fuel Cells (MCFCs) Solid Oxide Fuel Cells (SOFCs) and compares them with Internal Combustion Engines (ICEs) and micro-turbines (MTs). Operational data from six industrial-scale plants and from a pilot plant was collected to simulate the performance of these Energy Conversion Systems in twelve scenarios, built based on two WWTP sizes (100,000 and 500,000 PE) and two biogas qualities ($H_2S$ 2500 and 250 $ppm_v$). Comparisons were focused on technical (Normalized Saved Fossil Energy and percentage of energy self-sufficiency) and economic (Levelized Cost of Energy and Payback Period/Internal Rate of Return) indicators. MCFCs showed the highest technical performance, improving the electrical self-sufficiency of the WWTP around 60% compared to conventional cogeneration. However, to date, ICEs are still the most economically profitable alternative, as payback periods of fuel cell projects are 4 times larger. The high investment cost and the low stack durability are the key parameters to be improved for industrial deployment of fuel cell systems in WWTPs.



## 1. Introduction

Within the framework of sustainable development, energy in Waste Water Treatment Plants (WWTPs) must be considered not only in terms of consumption reduction, but also in terms of "green" energy production. Consumption reduction is achieved through energy efficiency measures; which are usually carried out through energy auditing, smart process control and replacement of old equipment [1]. On the other hand, "green" energy production using the biogas produced during the anaerobic digestion of sewage sludge to produce electricity has turned into an appealing alternative in recent years. Fig. 1 shows the configuration of the municipal WWTP considered in this study; with activated sludge in the sewage line and anaerobic digestion in the sludge line. Both power consumption and production (electrical and thermal) elements are indicated.

For long time, chemical energy contained in the biogas was transformed into electricity in Internal Combustion Engines (ICEs) and more recently in Micro-Turbines (MTs) [2–5]. ICEs are engines in which the combustion of the fuel inside the combustion chamber causes the expansion of the high-temperature and high-pressure gases, which apply a direct force onto some component of the engine (i.e.: piston; Otto/Diesel thermodynamic cycle). ICEs are available in a great range of sizes (from a few $kW_e$ to over 4 $MW_e$) and are used in a variety of applications such as standby and emergency power, peaking service, intermediate and base-load power and Combined Heat and Power (CHP). On the other hand, MTs are small electricity generators that can burn gaseous and liquid fuels to create high-speed rotation that turns an electrical generator (Brayton thermodynamic cycle). The size range for MTs is from 30 to 250 $kW_e$ and can be used for in power-only generation or for CHP [3].

However, both ICEs and MTs have a limited electrical efficiency (25–35%) due to the Carnot efficiency limitation [6,7]; and heat recovery in these systems is becoming an important feature to increase the overall energy efficiency. High-temperature fuel cells are thus becoming one of the most promising alternatives. Fuel cells are electrochemical devices that directly convert the chemical energy within the fuel into electrical energy; without the intermediate steps of producing heat and

*Abbreviations:* CAPEX, capital expenditures; CHP, combined heat and power; ECS, energy conversion system; FIT, feed-in-tariff; ICE, internal combustion engine; IRR, internal rate of return; LCE, levelized cost of energy; MCFC, molten carbonate fuel cell; MT, micro-turbine; NSFE, normalized saved fossil energy; OPEX, operational expenditures; PAFC, phosphoric acid fuel cell; PE, population equivalent; PEMFC, proton exchange membrane fuel cell; PER, primary energy ratio; PP, payback period; SOFC, solid oxide fuel cell; WWTP, waste water treatment plant.

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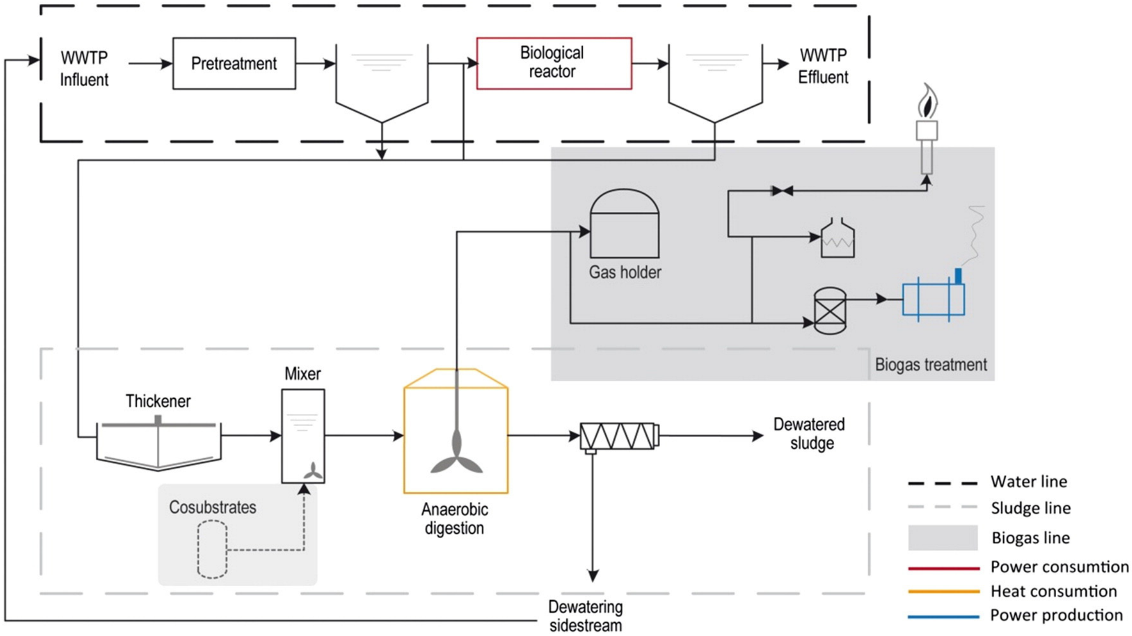


**Fig. 1.** Process flow schematic of the WWTP and boundaries considered in this study.

mechanical work of the previously described conventional power generation methods; hence they have greater electrical efficiencies and lower adverse exhaust emissions [8,9]. As a result, biogas utilization in fuel cells combines a high-efficiency technology for electrical generation and a renewable fuel, efficiently contributing to reduce greenhouse gas emissions and depletion of resources. Fuel inlet requirements for fuel cells are very stringent because several compounds (p.e.: sulfur, silicon, halogenated, etc.) are poisonous and harmful for all fuel cell types, affecting fuel cell catalytic processes and stack lifetime, and must be removed from the biogas [10–13]. Therefore, a thorough biogas treatment stage is always necessary upstream the cell [14].

High-temperature fuel cells, such as Molten Carbonate Fuel Cells (MCFCs) and Solid Oxide Fuel Cells (SOFCs), have larger fuel flexibility, accepting not only hydrogen but also other fuels as syngas, natural gas and biogas [15–17]. Furthermore, differently from low-temperature fuel cells, such as Proton Exchange Membrane Fuel Cells (PEMFCs) and Phosphoric Acid Fuel Cells (PAFCs), carbon monoxide is not a poison for these systems [18–20], but, on the contrary, it can be used as a fuel; hence its removal is not necessary [21]. Finally, biogas reforming in high-temperature fuel cells can be carried out within the fuel cell system (and not externally); which improves the overall energy balance [22–24]

Notwithstanding several fuel cell demonstration or industrial projects in the range of 25 $kW_e$ up to 2 $MW_e$ have been carried out [14, 25], fuel cell technology is not mature enough (and especially not for biogas), thus its performance, operational limits and reliability must be assessed to determine its application field in sewage treatment [26, 27]. Although it has become very popular in some European countries and in the USA in the last years [28–30], biomethane production (for gas grid injection) was not considered in this study because it is not an on-site energy recovery technology and it would not provide the electric and thermal energy needed for the WWTP operation, which makes the comparison not relevant in technical terms.

The objective of this paper is to investigate the current applicability, potential and limitations of biogas-powered high-temperature fuel cells and its comparison to conventional CHP technologies based on the technical and economic assessment of different scenarios based on two WWTP sizes and two different biogas compositions.

## 2. Methodology

### *2.1. Biogas energy recovery plants auditing and technology provider data collection*

6 audits on full-scale WWTPs with a configuration very similar to Fig. 1 were conducted in the USA (2 plants), Germany (1 plant), Italy (1 plant) and Spain (2 plants); collecting the most relevant technical and economic operational indicators both from the biogas treatment technologies and the Energy Conversion Systems (ECS) implemented on-site. Data was collected from historical databases from the operators and its quality was minimum one-year averages. In addition, the SOFC system was assessed at pilot scale in a 2.8 $kW_e$ plant which was operated for 18 months in a WWTP in Spain. Details on pilot plant configuration and performance can be consulted elsewhere [31,32]. Biogas treatment technologies included gas–liquid absorption (scrubber); gas–liquid absorption with biological regeneration of the chemical agent (bio-scrubber); biogas drying through gas refrigeration to 5 °C; and solid-gas adsorption on iron sponge (for $H_2S$) and activated carbon (for siloxanes). Details on the operating principle for each biogas treatment technology can be consulted elsewhere [9,33,34]. Table 1 collects a brief description of the gas trains on the selected plants showing the different technologies targeted at each audit.

On the other hand, data from suppliers/manufacturers was also collected to consolidate and complement data from the audits; both for biogas treatment technologies; p.e.: Paques (Balk, the Netherlands), DMT (Joure, The Netherlands), Desotec (Roeselare, Belgium), Verdesis

**Table 1**
Description of the gas trains and energy conversion systems at the audited WWTPs.

| Audit | Biogas treatment | ECS |
|---|---|---|
| USA 1 | Scrubber + iron sponge + drying + activated carbon | MCFC |
| USA 2 | Drying + activated carbon | MT |
| Germany | Drying + activated carbon | MCFC |
| Italy | Scrubber + drying + adsorbent materials | ICE |
| Spain 1 | Bio-scrubber + drying + activated carbon | ICE |
| Spain 2 | Drying | ICE |
| SOFC pilot | Iron sponge + drying + activated carbon | SOFC |