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

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## HIGHLIGHTS

- A techno-economic appraisal of a SOFC system integrated to a WWT plant is given.
- The approach is based on a cost optimal generators dispatch.
- SOFCs may become cost competitive in thermally-optimised WWTPs.

## ARTICLE INFO

*Keywords:*
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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.

## 1. Introduction

Wastewater treatment is one of the most energy intensive public utilities, accounting for more than 1% of electricity consumed in Europe [1]. There are more than 23,000 wastewater treatment plants across Europe with at least secondary treatment [2], with an overall energy consumption and greenhouse gas emissions of approximately 15,000 GWh/yr and 27 $MtCO_2$-eq/yr, respectively [1,3]. Reduction of the energy use and emissions is a worthwhile part of broader deep decarbonisation strategies in place in Europe [4].

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 [5]. 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 [6–8] is the main prime mover of interest in this article due to the ability to generate electricity in the efficiency range of 50–62% [8].

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 [9,10]. 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

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**Nomenclature**

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

*Parameters*

| | |
|---|---|
| *af* | annualisation factor |
| *BCap* | boiler capacity, kWh |
| $BGi_t$ | biogas flow inlet at time *t*, 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 $kgCO_2$ |
| *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, $kgCO_2$ per kWh |
| $ep_t$ | electricity price at time *t*, € per kWh |
| *ge* | natural gas emission factor, $kgCO_2$ 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/year |
| *UMCb* | annual maintenance cost of boiler, € per kWh/year |
| *UOC* | annual clean up cost per generator, € per kWh/year |
| *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 variable*

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

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 2 and 3. Finally the model is applied leading to discussion of key results and conclusions.