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 (100000 and 500000 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.

Keywords: biogas; cogeneration; WWTP; SOFC, MCFC; fuel cells

List of 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

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 efficiencies 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. Figure 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.

Figure 1.

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 baseload 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 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 utilisation 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 Figure 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 ºC; 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.

Table 1.

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 (Courbevoie, France), Siloxa AG (Essen, Germany) and for CHP systems; p.e.: Jenbacher (Jenbach, Austria), Caterpillar (Peoria, IL, USA), Capstone (Chatsworth, CA, USA), Fuel Cell Energy (Danbury, CT, USA), SOFC Power (Mezzolombardo, Italy).

2.2. Scenarios description

Twelve scenarios covering the most common European scenario were simulated based on the criteria described in Figure 2.

Figure 2.

a) Two WWTP sizes: **100000 and 500000 Population Equivalents (PE):** These sizes were chosen because 100000 PE (wastewater flow 12350 m^3/day; biogas production 62.5 Nm^3/h) is the plant size capacity from where anaerobic digestion is usually implemented [35] and 500000

PE (wastewater flow 61500 m^3/day; biogas production 312.5 Nm^3/h) represents high capacity European plants [36].

Seasonal variations in biogas production were assessed by term (increases of -15% in Term 1; of +10% in Term 2; of +15% in Term 3; and of -10% in Term 4; respectively over average biogas production).

***b) Two biogas pollution levels on H_2S:* 2500 and 250 ppm_v H_2S:** These compositions represent biogas contamination levels commonly observed on sewage biogas in Europe [9, 37], depending on wastewater quality and treatment processes implemented. In addition to sulphur contamination, siloxanes concentrations of 10 mgSi/Nm^3 were considered. The CH_4 content was set at 65% for all scenarios (rest CO_2) as a standard average composition. Biogas treatment systems were designed for each specific case according to the different pollution levels and the quality requirements of ECS.

c) Four different CHP technologies ECS: Internal Combustion Engine, Micro-turbine (only for the 100000 PE plant size), Molten Carbonate Fuel Cell and Solid Oxide Fuel Cell (again; only for the 100000 PE plant size as the technology is not commercially ready yet) were considered. WWTPs were supposed to be equipped with a flare (for handling biogas production excess and during ECS maintenance or downtime periods) and a boiler (coupled to a sludge heating Heat Exchange Network); hence these costs were not considered in the investment. Thermal unbalances between heat production at the CHP unit and heat demand are satisfied with natural gas consumption.

2.3. Technical and economic indicators

A wide range of indicators has been used to assess the technical and economic performance of a biogas energy recovery train [38-43]. In this study, the following six indicators were selected in order to compare the different scenarios:

Normalized Savings Fuel Energy (NSFE): represents the primary energy that would have been required in a yearly basis to generate the energy (electricity and heat) produced with biogas. Saved fossil energy is divided by the biogas and natural gas energies (represented by the lower heating value) in order to normalize the result, allowing the direct comparison of different WWTP sizes. This indicator, determined as shown in Equation 1, assesses the overall performance (electrical and thermal) of the Energy Conversion System (ECS) regardless the WWTP size.

$$NSFE = \frac{E\frac{1}{PER_E} + H\frac{1}{PER_H}}{E_{Biogas,CHP} + E_{NaturalGas,Boiler}} \qquad \text{(Eq. 1)}$$

where: E and H are respectively the electricity (kWh$_e$/year) and thermal energy production (kWh$_t$/year) at the cogeneration unit; E$_{biogas,CHP}$ and E$_{NaturalGas,Boiler}$ are respectively the primary energies of biogas lead to the CHP unit and natural gas lead to boiler (kWh$_{th}$/year); and PER_E and PER_H are respectively the Primary Energy Ratios (i.e.: fossil fuel consumption per unit of energy produced) for electricity and heat. PER$_E$ accounted for 0.528 according to the Ministerio de Energía, Energía y Turismo [44]; and PER$_H$ can be calculated just as the amount of fuel required to generate the respective thermal energy; that is, basically, the efficiency of a boiler, which is fixed at 0.9 [45].

Energy self-sufficiency in WWTPs (%): standing for the ratio produced energy/energy demand (**electrical and thermal separately** as indicated in Equations 2 and 3 respectively). Electricity is basically required for aeration in the biological reactor and pumping in wastewater treatment [46, 47], while heat is necessary for digester's heating. Both energy consumptions present seasonal variability and they were assessed by term (T1, T2, T3 and T4). Increases of -15% in T1; of +10% in T2; of +15% in T3; and of -10% in T4; respectively over the average sewage treatment flow rate were established. On the other hand, air temperatures were set at 5ºC (T1), 15ºC (T2), 25ºC (T3) and 10ºC (T4). As a result, this indicator does not only take into account the energy performance of the ECS but also of the WWTP itself, because the energy demand in WWTPs is dependent on several variables (p.e.: WWTP size, existing processes, energy efficiency of the pieces of equipment, WWTP load, etc.). Within these considerations, this indicator actually assesses the precise and specific implementation of the ECS in sewage treatment.

$$Electrical\ \ self-sufficiency = \frac{E}{E_{WWTP}} \qquad \text{(Eq. 2)}$$

$$Thermal\ self-sufficiency = \frac{H}{H_{WWTP}} \qquad \text{(Eq. 3)}$$

where: E_{WWTP} and H_{WWTP} are the electricity (kWh_e/year) and thermal energy (kWh_t/year) demands in the WWTP. Only thermal energy demand for digester heating was considered.

Levelized Cost of Energy (LCE): specific cost to run the biogas energy recovery train; i.e.: both the biogas treatment and the ECS, expressed in c€/kWh_e and calculated as depicted by Equation 4 [48, 49]. A direct comparison of this cost with the electricity feed-in-tariff (FIT) allows envisaging the profitability of the project. A time horizon of 20 years was selected.

$$LCE = \frac{\sum_{t=0}^{N} \frac{(CAPEX_t + OPEX_t)}{(1+i)^t}}{\sum_{t=0}^{N} \frac{E_t}{(1+i)^t}} \qquad \text{(Eq. 4)}$$

where: $CAPEX_t$ and $OPEX_t$ are the investment and operational costs expended on year t (c€/year); and i is the Interest rate (which was considered of 8%). Yearly OPEX were updated with the last year-on-year rate (which was considered of 3%)

Payback Period (PP): period of time required to recover the funds expended in an investment; i.e.: years required to make the accumulated cash flow equal to the CAPEX of the project (Equation 5).

$$CAPEX = \sum_{t=1}^{Payback\ Period} (Incomes_t - OPEX_t) \qquad \text{(Eq. 5)}$$

Internal Rate of Return (IRR): discount rate at which the net present value of the costs of the investment equals the net present value of the benefits of the investment (Equation 6). PP and IRR are two typical criteria used to measure and compare the profitability of investments; among others such as the Net Present Value (NPV).

$$0 = \sum_{t=0}^{N} \frac{Incomes_t - OPEX_t}{(1+IRR)^t} \qquad \text{(Eq. 6)}$$

where $Incomes_t$ are the incomes generated by the project in year t (k€/year); which similarly to $OPEX_t$ were yearly updated with the last year-on-year rate (3%).

Taxes were not considered in the economic calculations; hence PP and IRR were both calculated from Earnings Before Taxes (EBT).

2.4. Modelling of the biogas energy recovery train

A biogas energy recovery calculation model was developed to standardize the technical and economic calculations for the twelve scenarios. Figure 3 shows the different modules of the model; indicating the most relevant inlets and outlets for each module and its interactions. As it is shown, Module 1 calculates the electricity requirements for wastewater treatment; and the anaerobic digester thermal demand for sludge heating as a function of digester geometry, insulation materials and ambient temperatures (according to [49]). Module 2 calculates the performance of the biogas treatment technologies to reduce the concentration of biogas contaminants (H_2S, siloxanes and moisture) to the specific requirements of each CHP unit depending on the raw biogas concentration. Module 3 determines both the electric and thermal performance of the CHP unit as a function of the treated biogas composition and the CHP unit load (power introduced/nominal power). Modules 4 and 5 provide the CAPEX and OPEX assessments of the biogas energy recovery train on a yearly basis (for the time horizon of 20 years) taking into account all costs involved in the design and construction (CAPEX) and operation (OPEX) of the train. Finally, Modules 6 and 7 calculate the values of the six indicators described in section 2.3 in order to compare the different scenarios as a function of all previous calculations.

Figure 3.

An example of the model use and the calculations at the different modules for scenario D1 (500000 PE, H_2S 2500 ppm_v, Internal Combustion Engine) is presented in Table S1 of the Supporting Information.

Table S1.

3. Results and Discussion

3.1. Data collection of operational indicators from the audits

The technical and economic indicators of the different biogas treatment and energy conversion technologies/processes collected at the full-scale audits are summarized in Table 2. Two values are presented for some of the indicators as a result of differences associated to the sizes of the equipment.

Table 2.

3.2. Definition of the energy recovery train of the different scenarios

Biogas treatment systems were designed according to the decision-tree showed in Figure 4.

Figure 4.

Main desulphurisation (down to 250 ppm_v) followed by siloxanes polishing (down to 0.1 $mgSi/Nm^3$) was selected for those ECS with more tolerant sulphur limits (i.e.: ICEs and MTs). On the other hand, for ECS having very stringent quality requirements (i.e.: MCFCs and SOFCs), a more complex three stage treatment system was adopted: main desulphurisation (down to 250 ppm_v) followed by H_2S polishing (down to 1 ppm_v) and siloxanes polishing (down to 0.1 $mgSi/Nm^3$). For each adsorbent material unit, two filters were placed in series with reversing capability (lead-lag operation) as this configuration provided the possibility to operate a single bed while the other bed was changed out or regenerated; ensuring maximum availability of the system. A dryer was also installed upstream the adsorption beds in order to condense moisture from the biogas. Bio-scrubber, a technology with higher CAPEX and lower OPEX, was only considered for main desulphurisation at the 500000 PE WWTP; while caustic scrubber, a technology with lower CAPEX and higher OPEX, was considered at the 100000 PE WWTP.

On the other hand, sizing of the ECS was conducted based on the available systems on the market and technical data sheets from manufacturers. ICE technology is available in a wide range of power sizes: 249, 330, 499, 844, 1065, 1189, 1600 and 3000 kW_e (Jenbacher; [51]); and 143, 235, 453, 600, 777, 1041, 1200, 1312, 1560, 2039, 3333 and 4300 kW_e (Caterpillar, [52]). On the other hand, micro-turbines are available in modular 30, 60 and 200 kW_e units (Capstone; [53]), while MCFCs are available in two possible power sizes; namely 300 kW_e and 1.4 MW_e (Fuel Cell Energy, [54]). No commercial SOFC units are available today for the WWTP sizes studied in this study (systems are in the range of few kW_e; SOFC Power, [55]) hence a modular unit of 50 kW_e was envisaged. The nominal electrical power of the ECS for the different scenarios is collected in Table 3. In addition, the average electrical power production during the 4 terms (and the corresponding load) is also indicated.

Table 3.

Average loads greater than 80% are obtained, indicating that the nominal power of the ECS matches the biogas energy potential most of the time. Terms with higher biogas production (T2 and T3) result in the operation of the ECS at loads of 100% and some biogas being diverted to the flare. The only exception is the MCFC unit on the 100000 PE WWTP, which was oversized as the smallest power size available in the market is 300 kW_e; which is too large for the biogas production of this plant. As it will be latter shown, this oversized ECS will have a negative impact on the economic balance of this scenario.

3.3. Technical assessment of the scenarios

Tables 4 and 5 collect the NSFE and the energy self-sufficiency (electrical/thermal) of the scenarios assessed based on the WWTP size and biogas pollution level.

Table 4.

Table 5.

As it can be observed when comparing A/B vs C/D scenarios, the effect of WWTP size is important in ICEs performance; as increments of 10 – 12% in NSFE and of 20 – 22% in electrical self-sufficiency are respectively observed because ICEs perform more efficiently at larger power sizes. The higher NSFE observed at C/D scenarios confirms that the WWTP size positively influences the overall performance of the ECS. Contrarily, in the case of fuel cells, an increase of NSFE and energy self-sufficiency is not observed with increasing WWTP size because electrical and thermal performances are almost independent of its nominal power.

NSFE values larger than 1 are obtained for MCFCs on all scenarios which indicates that fossil fuels savings exceed biogas production as a result of the high overall cogeneration efficiency. ICEs at 500000 PE WWTP also present NSFE above 1.

The comparison B/D vs A/C displays the effect of the biogas pollution level; showing a slight reduction of the technical indicators at contaminated scenarios because the biogas treatment installed is more complex; which on the one hand increases its energy consumption and on the other reduces the availability of the entire energy recovery train; thus the overall net electric and thermal productions decrease. Notwithstanding, the effect of this variable is less significant than in the case of WWTP size as the contribution of electric consumption in biogas treatment systems is much smaller than electricity production at the ECS.

Finally, the comparison of the different ECS technologies depicts that MCFCs has the highest performance compared to other CHP technologies. At the 100000 PE WWTP, NSFE and electrical self-sufficiency are respectively 30 – 32% and 60 – 63% higher than ICEs. Notwithstanding, the difference in performance of ICEs and MCFCs is smaller at the 500000 PE WWTP for the reasons exposed above. MTs provide the smallest electrical production of the assessed ECS, consistent with their reduced electrical performance; while greatly exceed the thermal demand of sludge heating. Therefore, they can be a very attractive option in WWTPs in which additional heat demands (p.e.: office building heating; sludge drying, etc.) are required. Finally, SOFC systems show slightly larger electrical performance than conventional CHP technologies but are not able to match thermal demand. As a result, the NSFE of SOFCs is similar to the values obtained for ICEs and MTs; showing that, in spite of the still low development level, SOFC technology is currently competitive in technical terms to conventional cogeneration, confirming good prospects for future industrial deployment.

It must be mentioned that WWTPs' electrical self-sufficiency cannot be achieved with any of the present CHP technologies; as values obtained range between 40 and 75%. Although other studies [27, 56] overview the potential of achieving an energy-neutral (and even an energy-positive) wastewater treatment, it is necessary not only to implement high efficient biogas energy conversion technologies but also on other strategies such as boosting biogas production (p.e.: via co-digestion with other substrates or sludge pre-treatments; [57, 58]) and/or implementing energy efficiency measures and new processes to reduce consumption [59, 60]. On the other hand, thermal demand for digester heating can be satisfied on average for the tested range of temperatures as thermal self-sufficiencies are very close or well over 100% with the exception of SOFCs. However, it should be taken into account that at cold seasons (i.e.: winter time), natural gas consumption is required while at the warm seasons (i.e.: summer time) large quantities of waste heat cannot be recovered and are thus discharged into the atmosphere.

3.4. Economic assessment of the scenarios

Table 6 and Figure 5 show the LCE and payback periods/internal rate of return for the scenarios assessed based on the WWTP size and biogas pollution level.

Table 6.

Figure 5.

The comparison of A/B vs C/D shows that payback periods are approximately reduced to the half by increasing WWTP size for all ECS as a result both of CAPEX and OPEX reduction with increasing electric power. This is consistent with the values obtained for the LCE; which are also reduced consequently. The economic profitability of MCFC systems in the 100000 PE WWTP is significantly smaller than in the 500000 PE WWTP not only because of the economy of scale effect but especially because the fuel cell is oversized to match the biogas energy potential (which means that both CAPEX and stack replacement costs are oversized).

On the other hand, the influence of the pollution level (B/D vs A/C) in the economic balance is more significant at the 100000 PE rather than at 500000 PE WWTP. On the former, improvements on the LCE for clean gases of around 40% for conventional CHP technologies and of around 20% for fuel cells are observed when compared to polluted gases. Differently, at 500000 PE WWTP, improvements are a bit more moderate; i.e.: 22% and 10% respectively.

The comparison of the different ECS shows that nowadays ICEs are the most profitable option to be deployed at WWTPs, with payback periods ranging between 2 and 5 years depending on the size and level of biogas pollution. As it is also depicted, micro-turbines are not competitive to ICEs; hence their application range may probably take place at WWTPs less than 100000 PE. In the case of MCFCs, despite the payback period is larger than for ICEs (around 4 times), it is concluded that the technology can be profitable and marketable (as it has been proved with the existing installations in USA and Germany). Although the profitability of MCFCs in this study was lower at 100000 PE WWTP; fuel cell application is expected to play a more significant role in small- and medium-scale WWTPs as their performance on these sizes clearly exceeds ICEs performance. Finally, SOFC systems are still not economically competitive today as they show electrical efficiencies comparable to conventional CHP technologies with larger investment costs.

3.5. Sensitivity analysis

According to the results obtained, the high CAPEX (k€/kW$_e$) and the low stack replacement rate (years) are the key variables affecting the economic assessment of fuel cell projects (4.5 k€/kW$_e$ and 5 years respectively). Chalk and Miller [61] and Elmer et al. [62] also identified these two variables as two of the key challenges for fuel cell implementation. A sensitivity analysis of the effect of these two variables on the IRR was conducted to determine the threshold levels at which MCFC technology would be economically profitable compared to ICE (Figures 6 and 7). IRR of ICEs scenarios (A1, B1, C1 and D1) are depicted as horizontal lines.

Figure 6.

Figure 7.

As it is depicted, the independent effect of the two variables is not sufficient to balance the economic profitability of MCFCs and ICEs projects. On the one hand, at a constant stack durability of 5 years, it is necessary to reduce the investment costs at around 1 k€/kW$_e$ (a 4.5-fold reduction) to balance the IRR of MCFCs and ICEs. On the other, at a constant investment cost of 4.5 k€/kW$_e$, it is not possible to balance IRR by increasing the stack durability. Although improvements on the investment cost are more effective compared to improvements on stack durability due to the sharper profile, it is concluded that new developments in fuel cell manufacturing should be aimed both at a reduction of the investment cost and an increase of stack lifetime.

4. Conclusions

Following audits on industrial-scale WWTPs and the operation of a pilot-scale unit, it was possible to assess the application field of high-temperature fuel cells and compare them to conventional CHP technologies. For all cogeneration systems, the impact of WWTP size on the technical and economic performance was more significant than the biogas pollution level.

MCFC systems are the most efficient cogeneration technology, especially at small and medium-scale WWTPs, showing Normalized Saved Fossil Energy values of 1.25 and an electrical self-sufficiency of 70% for the 100000 PE WWTP (this is around 30% and 60% respectively larger than conventional cogeneration). However, in the 500000 PE WWTP, the performance of ICEs is similar to MCFCs. Notwithstanding, payback periods of MCFC projects are 4 times larger than for ICEs; which today is still the most profitable technology for sewage biogas energy recovery.

SOFC systems, despite its low development level, have a comparable technical performance with ICEs; confirming the good prospects of this technology. However, the economic profitability is still far away from industrial deployment (further than MCFCs); hence the impact of this technology in sewage treatment is expected for the medium- or long-term.

Both the high CAPEX and the reduced lifetime of MCFC and SOFC systems should be improved before fuel cell can become a deployable technology in WWTPs, especially at small- and medium-scale plants. Fuel cell manufacturers and biogas producers should be involved together in research and development projects in order to overcome the identified performance limitations.

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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

Table 2. Technical and economic indicators collected from audits used for scenario evaluation

	Variable	**Value**	**Unit**	**Audit**
Technical	Electricity consumption wastewater treatment (600 gCOD/m^3)	0.5	kWh/m^3	Average 6 WWTP
	NaOH consumption caustic scrubber (@CO$_2$: 35%)	6	kgNaOH/kgH$_2$S	Italy
	Electricity consumption caustic scrubber	5.88	kWh$_e$/kgH$_2$S	Italy
	NaOH consumption bio-scrubber	2	kgNaOH/kgH$_2$S	Spain 1
	Electricity consumption bio-scrubber	7.43	kWh$_e$/kgH$_2$S	Spain 1
	Nutrients consumption bio-scrubber	0.15	L/kgH$_2$S	Spain 1
	Availability caustic scrubber/bio-scrubber	95	%	Italy, Spain 1
	Adsorption capacity iron sponge (H$_2$S)	0.3	kgH$_2$S/kg material	SOFC pilot
	Siloxanes removal efficiency drying (at 5ºC)	30	%	USA 1, Germany SOFC pilot
	Adsorption capacity activated carbon (siloxanes)	0.0025	kgSi/kg material	USA 1, Germany SOFC pilot
	Electricity consumption adsorbent materials	0.0001	kWh$_e$/Nm^3/filter	USA 1, Germany
	Electricity consumption drying (heat pump)	0.01	kWh$_e$/Nm^3	USA 1, Germany
	Availability dryer, activated carbon, iron sponge	100	%	USA 1, Germany SOFC pilot
	Thermal efficiency Boiler	90	%	Spain 1, 2
	Electrical efficiency ICE	31 – 37	%	Spain 1, 2, Italy
	Thermal efficiency ICE (low and high grade heat)	45 – 40	%	Spain 1, 2, Italy
	Availability ICE	96	%	Spain 1, 2, Italy
	Electrical efficiency Micro-turbine	28	%	USA 2
	Thermal efficiency Micro-turbine (high grade heat)	50	%	USA 2
	Availability Micro-turbine	98	%	USA 2
	Electrical efficiency MCFC	48	%	USA 1, Germany
	Thermal efficiency MCFC (high grade heat)	37	%	USA 1, Germany
	Availability MCFC	98	%	USA 1, Germany
	Electrical efficiency SOFC	34	%	SOFC pilot
	Thermal efficiency SOFC (high grade heat)	28	%	SOFC pilot
	Availability SOFC	98	%	SOFC pilot

Economic	Investment cost caustic scrubber	2.1 – 0.5	k€/(Nm^3/h)	Italy
	Investment cost bio-scrubber	2.6 – 0.6	k€/(Nm^3/h)	Spain 1
	Investment cost dryer + activated carbon + iron sponge	1.4 – 0.8	k€/(Nm^3/h)	USA 1, Germany
	Investment cost ICE	1.2 – 0.8	k€/kW$_e$	Spain 1, 2
	Investment cost Micro-turbine	1.8	k€/kW$_e$	USA 2
	Investment cost Fuel Cells (MCFCs, SOFCs)	4.5	k€/kW$_e$	USA 1
	Stack replacement rate Fuel Cells (MCFCs, SOFCs)	5	years	USA 1
	Investment cost Fuel Cell stack (MCFCs, SOFCs) (percentage over the entire Investment Cost)*	40	%	USA 1
	Investment cost Civil works	50 – 75	k€	6 WWTP
	NaOH cost (100%)	1	€/kg	Italy 1, Spain 1
	Nutrient solution cost	2.5	€/L	Spain 1
	Liquid waste treatment cost (treated in the same WWTP)	0.1	€/m^3	Average 6 WWTP
	Iron sponge cost	3.5	€/kg	SOFC pilot
	Activated carbon cost	2	€/kg	USA 1, 2, SOFC pilot
	Solid waste disposal cost (non-toxic)	50	€/kg	USA 1, 2, SOFC pilot
	Biogas treatment maintenance cost (caustic scrubber; bio-scrubber; dryer; activated carbon; iron sponge)	2 (<2 y) 5 (2 – 6 y) 10 (>6 y)	% over CAPEX	6 WWTP
	ICE maintenance cost (lubrication oil substitution, general maintenance)	1.3	c€/kWh$_e$	Spain 1, 2
	Micro-turbine maintenance cost (general maintenance)	1	c€/kWh$_e$	USA 2
	Fuel Cell maintenance cost (general maintenance)	0.5	c€/kWh$_e$	USA 1
	Man-power requirements	0.25 – 1	h/day	6 WWTP
	Man-power costs	20	€/h	6 WWTP
	Natural gas cost	4.5	c€/kWh$_t$	6 WWTP
	Electrical works cost	450	€/kW$_e$	Spain 1, 2, Italy
	Electricity Feed-in-Tariff (FIT)	12	c€/kWh$_e$	6 WWTP

* High-temperature fuel cell units basically consist of two modules: the electrochemical stack and the heat integration unit. As a result of progressive degradation over the time, the electrochemical stack needs to be substituted (stack replacement rate). Investment cost of stack exchange needs to be therefore considered over the length of the project.

Table 3. Nominal and actual electric power (kW$_e$) and ECS load of the different scenarios (%)

WWTP size and pollution level	ECS	Nominal Electric power ECS (kW$_e$)	Average Electric power ECS (kW$_e$)	Load ECS (%)
A and B	ICE	143	124	88
	MT	120 (2 x 60)	110	91
	MCFC	300	195	65
	SOFC	150	135	90
C and D	ICE	844	746	88
	MCFC	1200 (4 x 300)	975	81

(A = 100000 PE, 250 ppm$_v$; B = 100000 PE, 2500 ppm$_v$; C = 500000, 250 ppm$_v$; D = 500000 PE, 2500 ppm$_v$)

Table 4. Normalized Saved Fossil Energy of the different scenarios (kWh/kWh)

Scenario	A	B	C	D
ICE	0.96	0.92	1.07	1.02
MT	0.92	0.87	Not applicable	
MCFC	1.29	1.22	1.28	1.22
SOFC	0.95	0.90	Not applicable	

(A = 100000 PE, 250 ppm$_v$; B = 100000 PE, 2500 ppm$_v$; C = 500000, 250 ppm$_v$; D = 500000 PE, 2500 ppm$_v$)

Table 5. Electrical/Thermal energy self-sufficiency of the different scenarios (%)

Scenario	A	B	C	D
ICE	46 / 123	44 / 116	56 / 109	53 / 103
MT	42 / 134	40 / 128	Not applicable	
MCFC	75 / 103	71 / 98	75 / 103	71 / 98
SOFC	52 / 76	49 / 73	Not applicable	

(A = 100000 PE, 250 ppm$_v$; B = 100000 PE, 2500 ppm$_v$; C = 500000, 250 ppm$_v$; D = 500000 PE, 2500 ppm$_v$)

Table 6. Levelized Cost of Energy of the different scenarios (c€/kWh$_e$) (1 € = 1.08 USD)

Scenario	A	B	C	D
ICE	6.1	10.4	4.6	5.9
MT	6.7	11.5	Not applicable	
MCFC	16.6	19.9	13.4	14.8
SOFC	15.2	19.4	Not applicable	

(A = 100000 PE, 250 ppm$_v$; B = 100000 PE, 2500 ppm$_v$; C = 500000, 250 ppm$_v$; D = 500000 PE, 2500 ppm$_v$)

Table S1. Model use and calculations at the different modules for scenario D1

MODULE OUTPUTS			
Module 2	Treated biogas flow and composition		312.5 Nm^3/h 65% CH_4; 250 ppm_v H_2S; 0.04 mgSi/Nm^3 siloxanes
	NaOH consumption		18753 kg/year
	Adsorbent material consumption		6342 kg/year
	Bleed production		360 m^3/year
Module 3	Electrical generation	Tot	5.96 GWh_e/year
		Q1	1.27 GWh_e/year
		Q2	1.65 GWh_e/year
		Q3	1.69 GWh_e/year
		Q4	1.35 GWh_e/year
	Thermal generation	Tot	6.45 GWh_t/year
		Q1	1.38 GWh_t/year
		Q2	1.79 GWh_t/year
		Q3	1.82 GWh_t/year
		Q4	1.46 GWh_t/year
Module 1	Electrical demand WWTP	Tot	11.23 GWh_e/year
		Q1	2.39 GWh_e/year
		Q2	3.09 GWh_e/year
		Q3	3.23 GWh_e/year
		Q4	2.53 GWh_e/year
	Thermal demand WWTP	Tot	6.35 GWh_t/year
		Q1	1.68 GWh_t/year
		Q2	1.73 GWh_t/year
		Q3	1.34 GWh_t/year
		Q4	1.69 GWh_t/year
	Natural gas requirements	Tot	25.580 Nm^3/year
		Q1	8.03 Nm^3/h
		Q2	0 Nm^3/h
		Q3	0 Nm^3/h
		Q4	3.65 Nm^3/h
Module 5	Total investment expenses		1506 k€
	Biogas treatment investment expenses		380 k€
	ICE investment expenses		675 k€
	Civil and electrical works, engineering		451 k€
Module 4	Total operational expenses		164 k€/year
	Biogas treatment operational expenses		67 k€/year
	ICE operational expenses		78 k€/year
	Man-power operational expenses		8 k€/year
	Natural gas operational expenses		11 k€/year
Module 6	Normalized Savings Fossil Energy		1.02
	Electricity self-sufficiency		53%
	Thermal self-sufficiency		103%
Module 7	Levelized Energy Cost		5.9 c€/kWh_e
	Payback Period		2.6 years
	Internal Rate of Return		41%

Figure captions_reviewed

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

Figure 2. Schematic description of the different scenarios typology for biogas energy recovery

Figure 3. Description of the different modules of the biogas energy recovery evaluation model

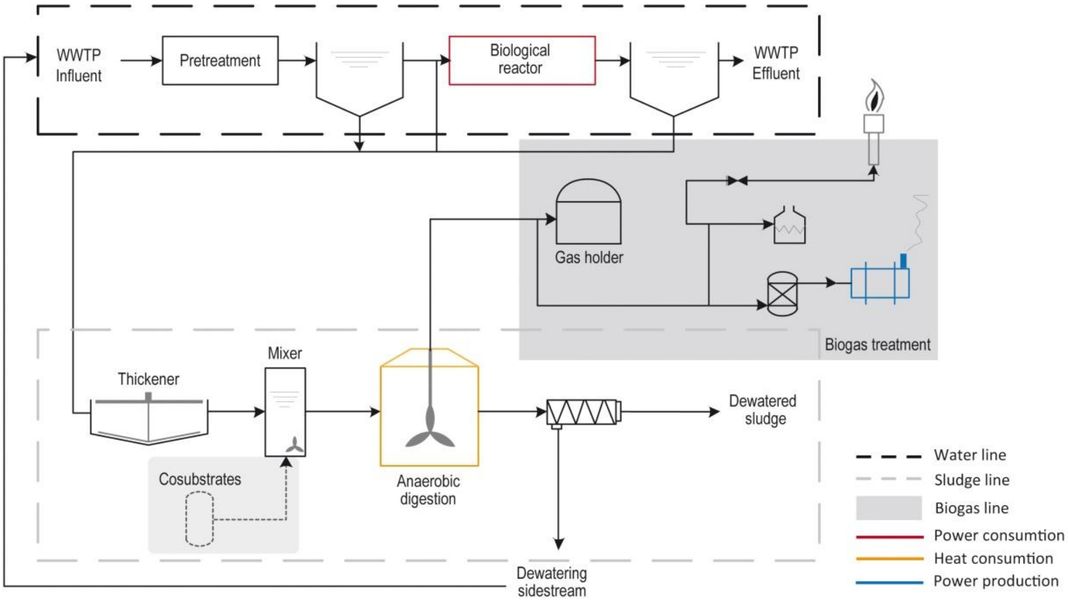
Figure 4. Schematic description of the decision tree for the selection of the biogas treatment technologies adapted to the selected ECS

Figure 5. Payback period (years) and Internal Rate of Return (IRR) for the different scenarios as function of the plant size and biogas quality. (A = 100000 PE, 250 ppm_v; B = 100000 PE, 2500 ppm_v; C = 500000, 250 ppm_v; D = 500000 PE, 2500 ppm_v)

Figure 6. Effect of the investment cost of MCFCs (k€/kW_e) on the IRR of the fuel cell project (stack durability 5 years). IRR of ICE projects is depicted as reference. (A = 100000 PE, 250 ppm_v; B = 100000 PE, 2500 ppm_v; C = 500000, 250 ppm_v; D = 500000 PE, 2500 ppm_v)

Figure 7. Effect of the stack durability of MCFCs (years) on the IRR of the fuel cell project (investment cost 4.5 k€/kW_e). IRR of ICE projects is depicted as reference. (A = 100000 PE, 250 ppm_v; B = 100000 PE, 2500 ppm_v; C = 500000, 250 ppm_v; D = 500000 PE, 2500 ppm_v)

Figure 1 in word format



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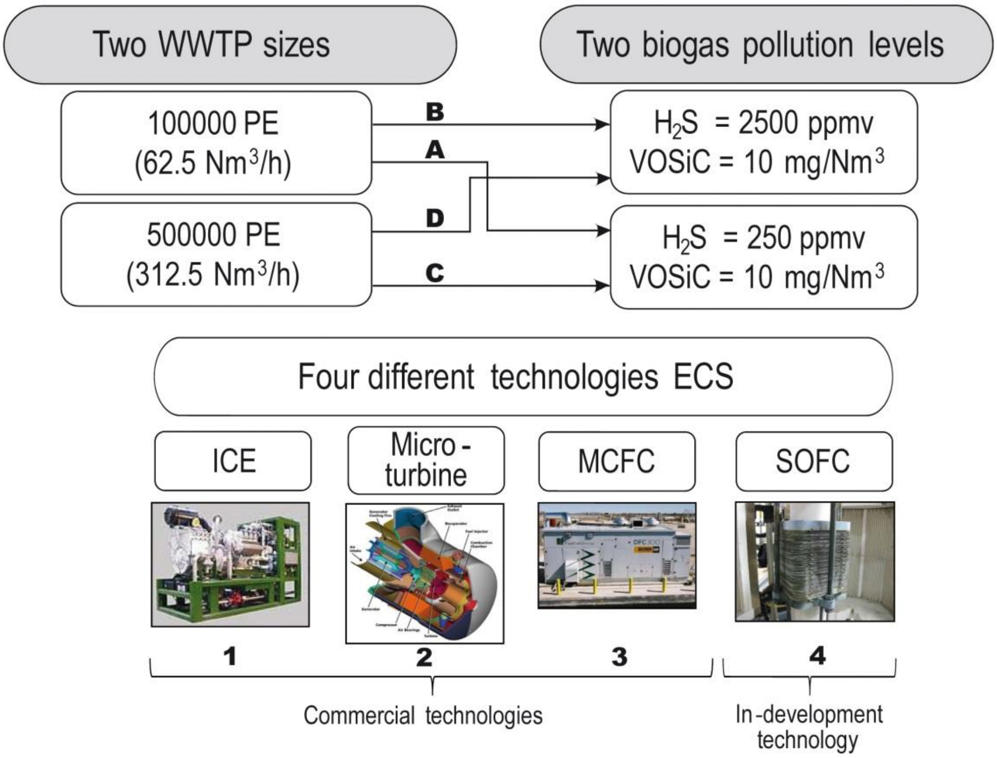

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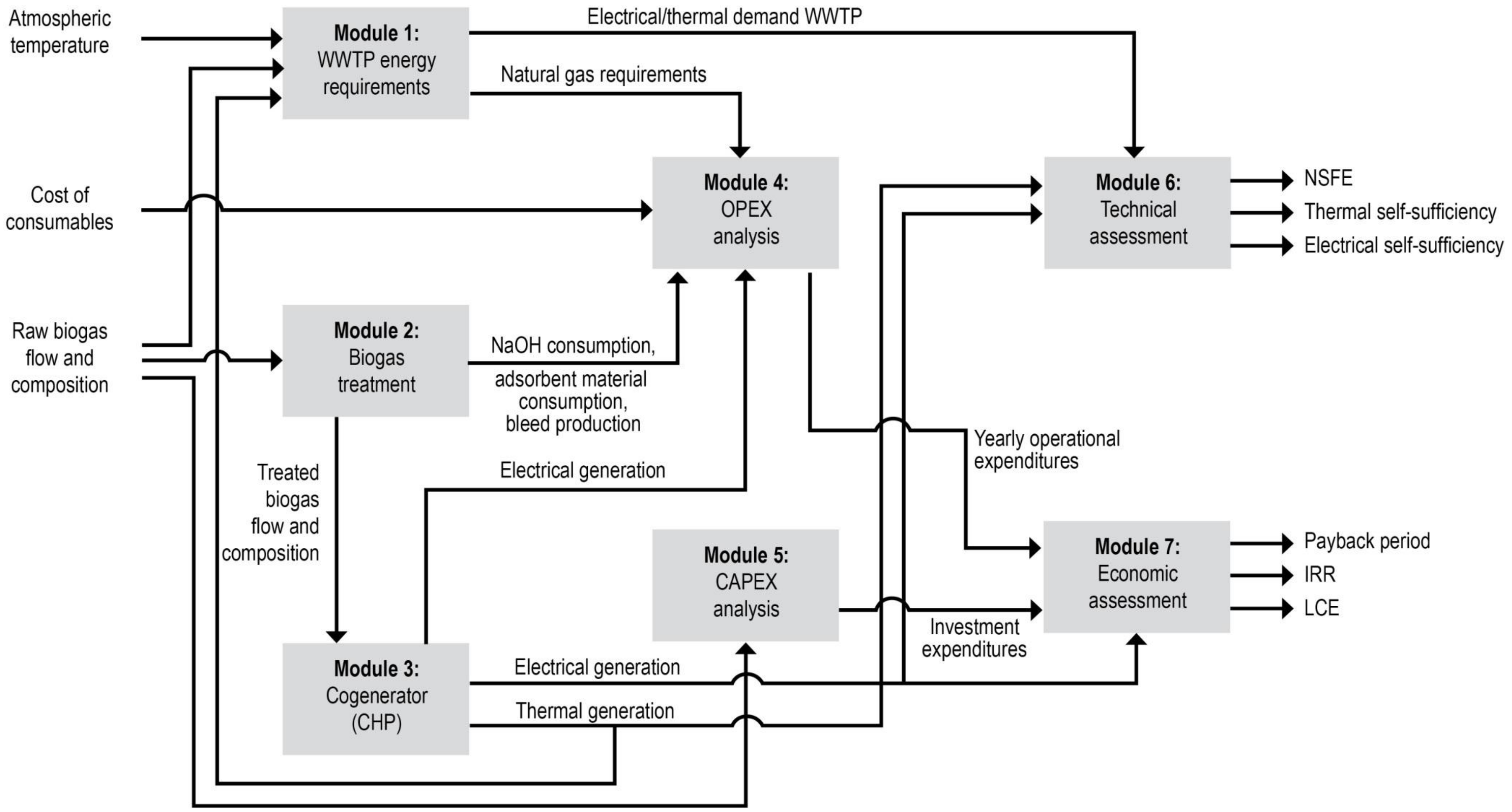

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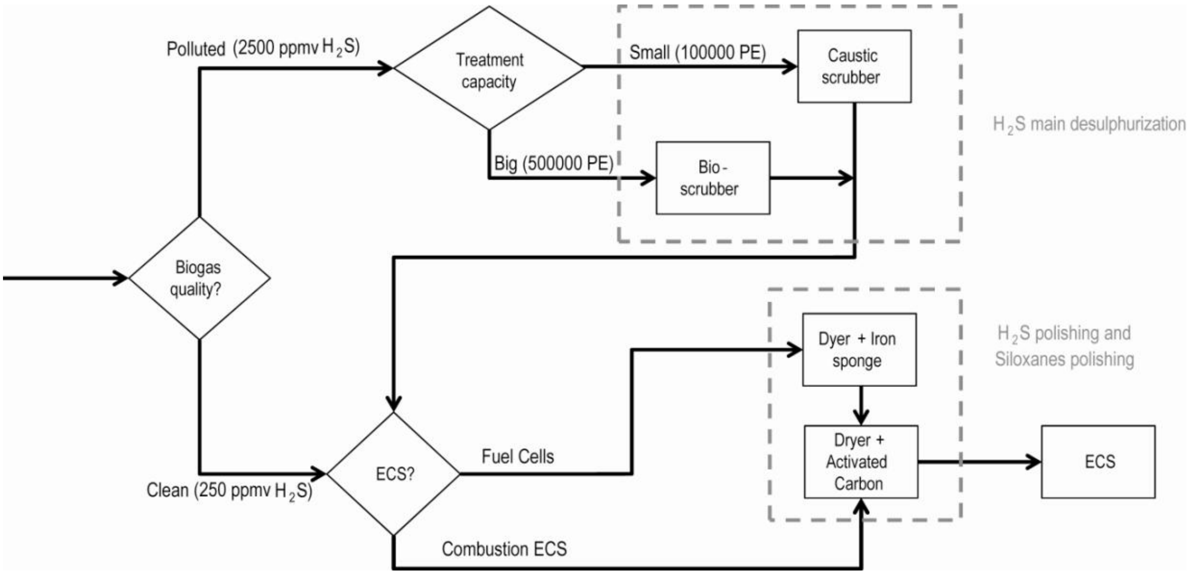

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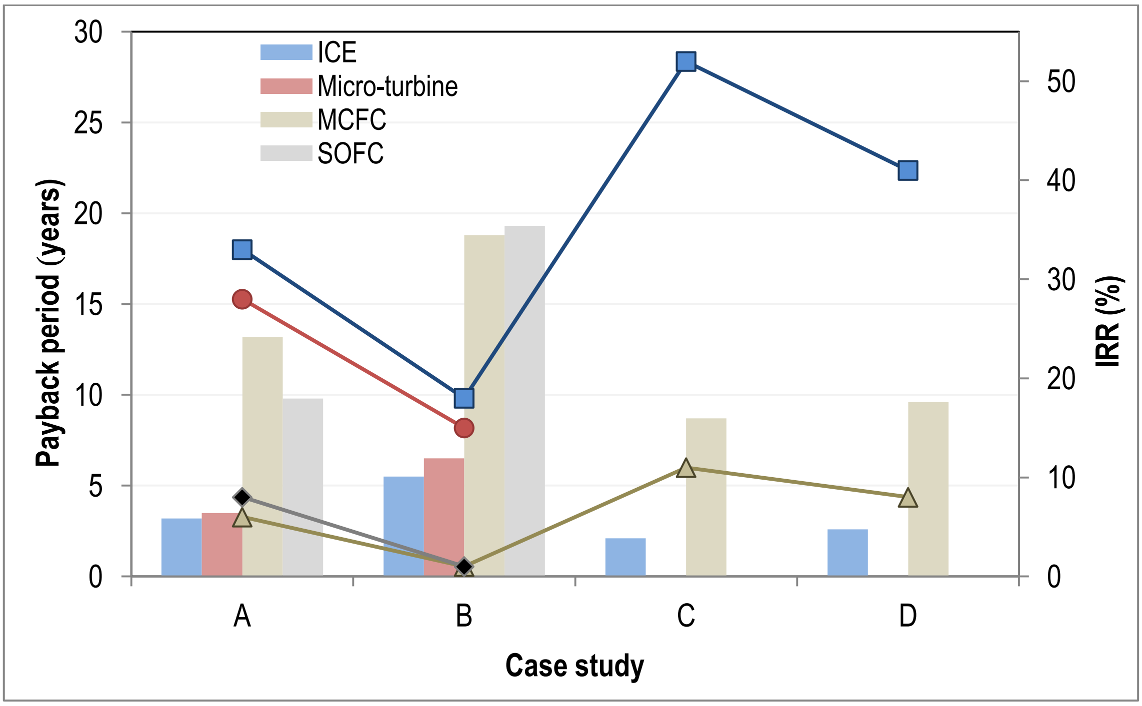

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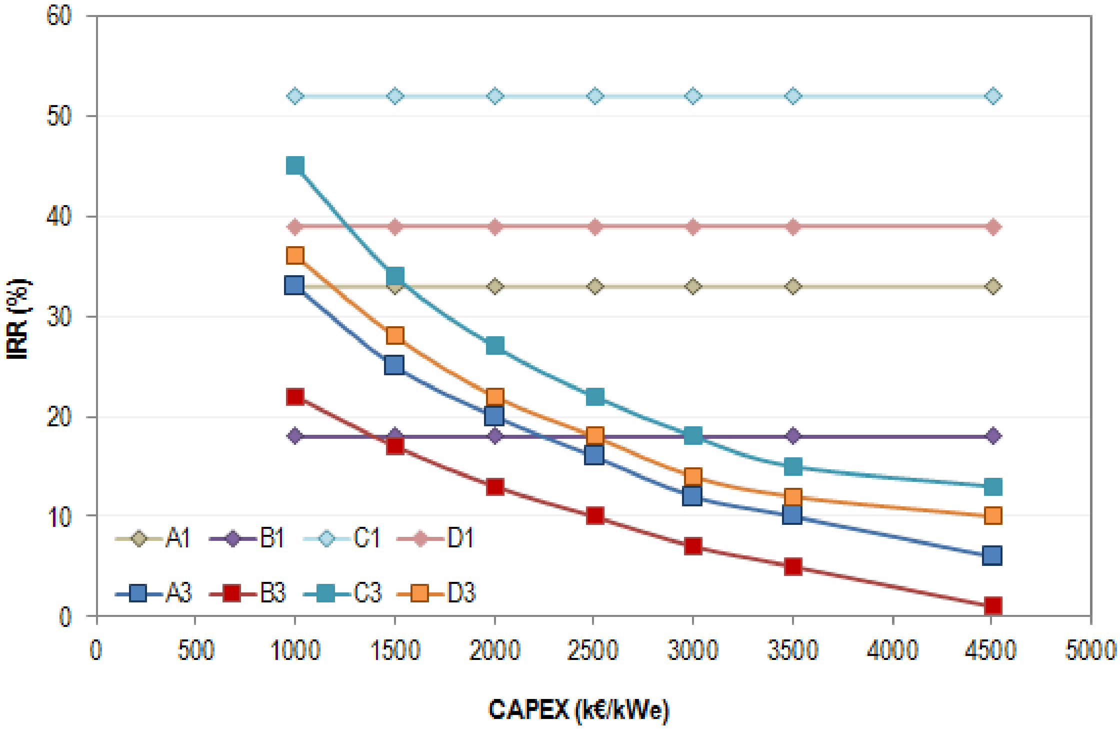

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