Economic assessment of a solid oxide fuel cell system for biogas utilization in sewage plants

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Abstract:

Fuel cells are likely to make their market introduction through high-efficiency applications in niche markets. A possible market for SOFC systems is therefore the utilization of low calorific biogas from sewage treatment plants. The feasibility of fuel cell application crucially depends on the gas cleaning system. A suitable system layout for SOFC integration is derived from an existing and long-term-tested fuel cell system for biogas utilization, providing a feasible design for gas cleaning for contaminant removal and data on different operation regimes. The resulting SOFC plant provides electricity and heat for on-site usage at the sewage plant by cogeneration. Applying the net present value method, the SOFC system is then analyzed at system level regarding its economic viability compared to a conventional CHP system. Costing for the different system components is made using real cost data and up-to-date estimates. Different design cases regarding the implemented system size and a sensitivity study concerning decisive economic parameters are used to provide robust decision measures. The study shows that economic feasibility of an SOFC system for biogas utilization can be achieved without any subsidies in the near future if SOFC system prices are reduced from 10000 to about 3500 EUR/kW$_{el}$.

Keywords:

Economic Analysis, Biogas, Cogeneration, Solid Oxide Fuel Cells

1 Introduction

Fuel cells offer the possibility of direct conversion of chemical energy to electric energy by electrochemical pathways. By avoiding the limitations of conventional power generation technologies, fuel cells offer a remarkably high efficiency with low environmental impact [1, 2]. These advantages have led to an increased industrial and governmental attention, thus providing fuel cell technology research and development (R&D) with increased funding [3–5] and stimulating international cooperation like IEA's advanced fuel cells and hydrogen implementing agreements [6]. But, even though much money was spent on R&D during the last 50 years, the commercialization is still delayed and economic feasibility yet not demonstrated [5, 7–9].

Based on the current status and future R&D needs, it is unlikely that fuel cells will make their market entry in the large-scale power generation sector. The current market conditions in this segment do not favor fuel cell system,s in general, due to the lack of subsidies and alternative evaluation methods to determine the cost of electricity [10]. Therefore, a market introduction through technological niches is more likely. In such market sections the technology can be tested, while it can be more expensive than the technology it replaces, if additional advantages like higher efficiencies are offered.

Among the various fuel cell technologies available, the solid oxide fuel cell (SOFC) technology offers various advantages, especially in stationary applications. High system availability time, flexibility of power generation, high efficiency, even in part load, and low specific emissions [1, 11] are just a few to mention.

A major challenge to exploit further market potential is to date the reduction of production cost. Looking at today's situation, small-scale SOFC demonstrators [5, 12] are already in use. These units contribute to cost reduction by three major factors: innovation (economies of scope), economies of scale and the learning curve effect [13, 14]. Therefore, these units help taking the transition step between pilot and very early commercial stages and the production at commercial scale.

If these effects are taken into account, then a possible market entry for SOFCs can be found in small (100 kW to 5 MW) combined heat and power (CHP) applications [8] where the investment cost difference to conventional technologies like gas turbines and gas engines becomes smaller. Likewise, the operating costs are lower due to higher efficiencies. Hence a typical area of fuel cell implementation, apart from domestic uses, can be found in the processing of low calorific gas which is used in small-scale power generation. Accordingly, steel production gases (coke gas, blast furnace gas and converter gas) [15] or sewage treatment gases (biogas) [16] can be advantageously processed by fuel cells.

The high methane content of biogas makes it particularly suitable for high-efficiency utilization in SOFCs [17]. During the past two decades extensive research has been conducted to prove the feasibility of SOFC application in this area. Detailed simulation models have been developed [18, 19] for conducting technological studies concerning fuel usage, system layout and optimal operation parameters. Additionally, the effect of biogas contaminants and their removal for secure SOFC operation has been addressed [20, 21]. Assessing the general question of techno-economic feasibility, recent studies [22, 23] have shown, that mature SOFC systems are generally favorable compared to conventional technologies for biogas utilization.

Sewage treatment plants offer a big market potential due to their large number of existing plants. Approximately, a population equivalent of 90,000 is needed to supply a 200 kW_{el} SOFC power plant with sufficient biogas [16] rendering a large set of potential sites. It seems viable that SOFC technology can therefore find its niche market in this segment due to its advantages of high efficiency power and heat generation being tailored to the inherent needs of sewage treatment plants. Moreover, for sewage plants in this capacity range, only one pilot project would be needed to double or even triple the production volume of producers and thus decreasing the production costs significantly through the economies of scale and scope.

Based on the large potential of biogas utilization, the present paper assesses the economic potential of using SOFC systems in contrast to conventional CHP systems for biogas utilization. Using data from an existing fuel cell plant for biogas utilization, the questions concerning system layout, gas cleaning options and cost data are addressed explicitly. Based on these data the question which system price makes SOFCs economically favorable to conventional solutions is answered with reduced uncertainty.

2 Methodology

In this paper, the net present value method is used to assess the economic measures of the biogas utilization solutions. After a short outline of the method, the approach for analyzing the SOFC and conventional CHP systems is developed.

2.1 Net Present Value and Net Present Cost

The net present value method is a dynamic investment calculation method with the purpose to find the most favorable investment out of a variety of possible options. The option with the highest net present value (*NPV*) or the lowest net present cost (*NPC*) is thereby the most profitable one [24].

The *NPV* of a project is calculated as the sum of the present values (*PV*) of all future cash flows (*F*). The present value describes the value of future earnings and expenses in the present. To calculate the present value of a certain future cash flow, it has to be discounted. Here all net present values refer to net present costs since no revenues are considered.

$$NPV = NPC = \sum_{k=1}^{m} PV_k = \sum_{k=1}^{m} \frac{F_k}{(1+i)^n} \tag{1}$$

The variable n represents the number of time periods and i is the calculation interest rate or discount rate.

To calculate the PV of cash flows that occur annually, such as revenues or operational expenditures, the capital recovery factor CRF [25] is helpful. With the annuity A being the constant annual cash flow over the given time period n, the PV of all these cash flows can be calculated using the following equation.

$$PV = A \cdot \left(\frac{i \cdot (1+i)^n}{(1+i)^n - 1} \right)^{-1} = \frac{A}{CRF} \tag{2}$$

The NPV method is a useful tool to make a sound investment decision, taking into account future income and investments as well as the time value of money [24]. Nonetheless, the net present value analysis is bound to monetary terms. Benefits of fuel cell systems like prestige, low environmental impact and know-how, cannot be assessed in monetary terms and thus not be reflected in the NPV calculations [16].

2.2 Approach to Analyze the Utilization of Biogas from Sewage Plants

Since sewage treatment is typically a service either by a state to its citizens or as a unit within an industrial plant, it cannot be justified by its profitability. Thus, the decisive question is how this service can be provided with the least possible *NPC*.

The calculation of the *NPC* will be separated into five different parts. The *NPC* consists of the capital expenditures (*CAPEX*), the operational expenditures (*OPEX*), cost of electricity (*CoE*), cost of heat (*CoH*) and possible subsidies. Even though the cost of the required additional electricity and heat are generally considered as a part of the *OPEX*, they have been taken aside due to their high influence on the *NPC*. An overview of the calculation procedure is shown in Table 1.

3 System Description

The system used for the economic assessment of SOFC integration in sewage treatment plants is derived from an existing and running fuel cell system [16]. It is based on phosphoric acid fuel cell (PAFC) technology and has been extensively tested at the sewage treatment plant at Cologne-Rodenkirchen [16]. Another option would be the installation of a conventional CHP system with a gas engine which is used for comparative purposes.

Table 1. Simplified model for NPC calculations.

Investment cost of the power system Investment cost of the gas cleaning system		*CAPEX*
Cost of maintenance Cost of service and inspection Labor	+	*OPEX*
Cost of additional electricity required	+	*CoE*
Cost of additional heat required	+	*CoH*
Supplementary payments (based on the KWKG)	−	Subsidies
	=	*NPC*

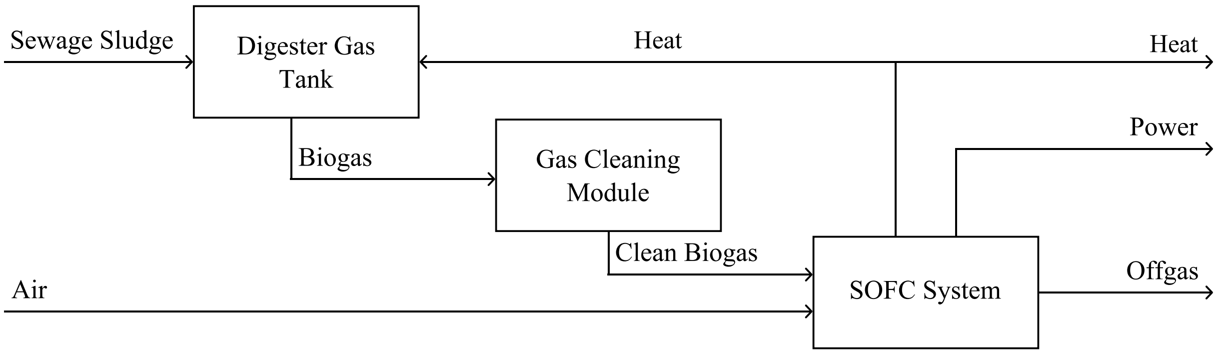

Fig. 1. Basic flowsheet of SOFC integration for digester biogas usage.

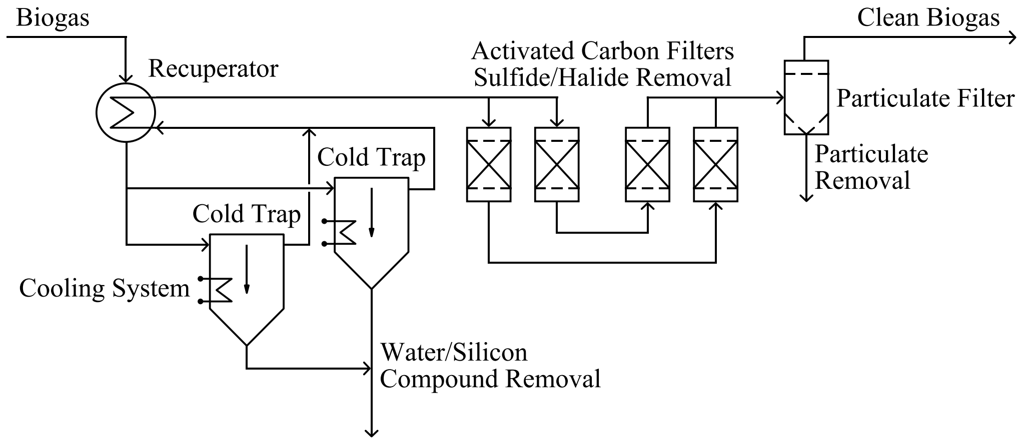

Fig. 2. Gas-cleaning system layout for the removal of contaminants from the digester gas [16].

3.1 System Description and Layout

The SOFC system processes biogas produced by digestion of sewage sludge. The plant layout of the biogas utilization train, as adopted from Adolph and Saure [16], is shown in Fig. 1. The same layout applies for the conventional CHP system as well.

The biogas generated by the digester is mainly a combination of 63 % methane (CH_4) and 37 % noncombustible gases [16], composed mainly of carbon dioxide (CO_2) and traces of nitrogen (N_2). To be usable for both power systems, the biogas has to be conditioned by cleaning.

The gas cleaning unit is a fundamental part of biogas processing. Impurities in the biogas may cause serious damage to the fuel cell and the equipment. Depending on the pollutant, the effects range from blocking the fuel flow, damaging the equipment or poisoning the fuel cell catalyst [16, 20, 26, 27]. These effects result in additional costs and lead to a reduced overall efficiency. Even though SOFCs are tolerant to fuel impurities, as SOFCs can process carbon monoxide and ammonia unlike other fuel cell technologies, contaminants should be removed to upgrade the biogas to fuel quality.

An often applied gas-cleaning system for biogas obtained from sewage plants is a cold trap in combination with active carbon filters [26, 27]. Such a cleaning unit has already been successfully applied in combination with fuel cells, e.g. at the sewage plant Cologne-Rodenkirchen [16]. The layout is shown in Fig. 2.

The cold trap system cools the biogas to a temperature lower than 243 K and removes water and silicon compounds by freezing. A recuperator for heat integration reduces the energy requirement significantly. The subsequent activated carbon filters remove sulfur and halogen components by adsorption. Two filters in sequence ensure maximum loading. A particle filter is applied at the end of the process to remove particles larger than 0.6 micrometers. The two parallel trains of the gas-cleaning system ensure continuous operation [16]. Table 2 illustrates the performance of the gas cleaning system regarding

Table 2. Biogas analysis of the Cologne-Rodenkirchen sewage plant before and after the gas cleaning unit as given by Adolph and Saure [16]. Additionally, these values are compared to the acceptable level of contaminants for SOFC operation [20, 21].

	Concentration		
Contaminant	Raw biogas	Clean biogas	SOFC tolerance [20, 21]
Siloxans	2.4 – 3.7 mg/Nm^3	< 0.18 mg/Nm^3	acceptable
Organic silicon	0.9 – 1.4 mg/Nm^3	< 0.07 mg/Nm^3	acceptable
Total sulfur	1.0 – 40.0 mg/Nm^3	< 1.0 mg/Nm^3	acceptable
Hydrogen sulfide	1.0 – 43.0 mg/Nm^3	< 1.0 mg/Nm^3	acceptable
Total halides	< 1.0 mg/Nm^3	< 1.0 mg/Nm^3	acceptable

the achievable contaminant concentrations compared to the maximum levels given for secure SOFC operation in the literature [20, 21].

The cleaned biogas is fed afterwards to the SOFC fuel cell system which uses air to oxidize the methane contained within the biogas in order to generate power and heat. As sewage treatment plants have a high energy demand, a part of the heat generated by the SOFC is fed to the digester for drying and heating purposes and the remaining part is used elsewhere on the plant site.

3.2 Scenario Description

The amount of biogas being processed for electricity and heat generation is highly influenced by the used capacity of the sewage treatment plant. Possible external influences are for instance rainfall and major events. Therefore, the SOFC system can be designed for different scenarios to meet different requirements of operation. For the sake of simplicity, an average base load of 65 Nm^3/h biogas production is assumed, with 90 Nm^3/h as peak load, based on the operational data given by Adolph and Saure [16].

As the gas storage has a limited capacity and gas flaring is restricted by law for cases of an emergency, peak load gas production has to be considered in the design of the power generating module. If the system is designed to cope with a 90 Nm^3/h, but is operated with average load of 65 Nm^3/h, the power system is running in part load most of the time. Fuel cells do not lose efficiency if operated in part load, but conventional gas engines of CHP systems do. Additionally, independent of the kind of power system installed, a high part load operation implies an overinvestment due to unused capacity. To approach this problem and the effects of varying power system dimensions, three different scenarios will are discussed in this work.

- Scenario 1: the systems are designed for an average throughput of 65 Nm^3/h biogas. Fluctuations are stored.
- Scenario 2: the systems are designed to cope with peak load biogas production of 90 Nm^3/h. Systems operate mostly in part load.
- Scenario 3: the systems are designed to cope with a peak load biogas production of 90 Nm^3/h. Deviations from the average biogas supply are compensated by natural gas (NG) supply to avoid part load operation.

A further difficulty in this calculation is the influence of subsidies and taxation, since these vary significantly depending on the regional or national laws. To obtain supraregional validity, a focus is put on a base case, where prices excluding value added tax (*VAT*) and other recoverable taxes are used and no subsidies are applicable.

Nonetheless, for the sake of completeness, the impact of subsidies is taken into consideration in a second case. The subsidies are chosen comparable to the German Cogeneration Act (Kraft-Wärme-

Kopplungs-Gesetz or KWKG). Ignoring taxations and specific regulations, the focus is put solely on additional revenues for electricity generated by CHP or FC systems.

3.3 Assumptions on System Integration into Sewage Plant Operation

Generated electricity is utilized inside the battery limits of the sewage treatment plant at 100 %. Hence no electricity is sold. About 70 % of the cogenerated heat is used on the sewage plant site. This is taking into account that the heat supply needed in summer is lower than in winter. If excessive heat is generated, it is dissipated and considered lost. In times of an additional heat demand, it is supplied by an existing and depreciated simple boiler that runs on natural gas.

3.4 Cost Estimation

The total capital investment (*TCI*) is equal to the sum of fixed capital investment cost and corresponding auxiliary equipment. Therefore, the assumed *TCI* for the power system include, apart from the purchase cost of equipment, all secondary costs such as for piping, control, transport, installation and commissioning. These factors are internalized in the *TCI* and are not listed separately. The CE plant cost index [28] is used to adjust the investment cost of each unit from their respective year to 2013.

- The *TCI* of the conventional CHP system are calculated based on the specific power-to-cost trends given in [29] for CHP modules that run on biogas.

$$\frac{TCI}{\text{EUR (2013)}} = 15164 \cdot \left(\frac{P}{\text{kW}_{\text{el}}}\right)^{-0.5361} \tag{3}$$

- The *TCI* of the SOFC system are estimated at 10,000 EUR/kW$_{\text{el}}$ [30] in 2013, with the stack accounting for circa 50 % of the cost. This also represents the cost expectation of the Sunfire GmbH for a small-scale SOFC CHP-system (100 kW to 1 MW) (Posdziech, personal communication, 2014)
- The *TCI* of the gas cleaning unit are 113,700 EUR (2013) [16] for the expected gas throughput. The gas cleaning equipment for a CHP system is assumed to be cheaper for a CHP system, due to the less stringent active coal replacement. The reduced value is set to 90 %.
- The *TCI* of the heat exchanger are calculated to be 81,800 EUR (2013).

For the CHP system the operation and maintenance cost (*OMC*) are separated into service and inspection (OMC_{s+i}), maintenance (OMC_m) and operation (OMC_{op}). The costs for operation and maintenance are calculated based on the VDI 2067 [31] guidelines using the following equations.

$$\left.\begin{aligned} OMC_{s+i} &= 0.02 \cdot TCI \\ OMC_m &= 0.06 \cdot TCI \\ OMC_{op} &= 100\,\text{h/a} \cdot LC \end{aligned}\right\} \quad \text{for CHP plants [31]} \tag{4}$$

For the SOFC system, the same factors are calculated based on assumptions to standardize the cost calculations. Since the operation of an SOFC system differs from a CHP system, the factors have to be adjusted. It is assumed that the stack has to be replaced after 7.5 years of operation due to deterioration effects and natural efficiency losses. Meanwhile, due to the simplicity and lack of moving parts in SOFC systems, the cost of service and inspection is expected to be quite low. As an approximation, it has been proposed to assume absolute costs equal to half of those for a conventional CHP.

$$\left.\begin{aligned} OMC_{s+i} &= 0.001 \cdot TCI \\ OMC_m &= 0.03 \cdot TCI \\ OMC_{op} &= 16\,\text{h/a} \cdot LC \end{aligned}\right\} \quad \text{for SOFC plants} \tag{5}$$

Table 3. Overview of assumptions made for the base case of economic system analyses.

Economic data			
Calculation interest rate	i		7 %
Average price change	r		0 %
Observation period	n		15 a
Chemical Engineering Index			390.6 (1999); 585.7 (2011); 567.6 (2013)
Costs			
Price of electricity from grid	c_{el}		0.144 EUR/kWh
Natural gas price	c_{NG}		0.048 EUR/kWh
Biogas price	c_{Biogas}		0 EUR/kWh
Labor cost	LC		45 EUR/h
Subsidies (surcharges as listed in the German KWKG)			
CHP above 50 kW until 250 kW			0.0400 EUR/kWh$_{el}$
CHP above 250 kW until 2 MW			0.0240 EUR/kWh$_{el}$
Fuel cells			0.0541 EUR/kWh$_{el}$
Sewage plant specific data			
Average electricity required			3,170,000 kWh/a
Average heat required			2,150,000 kWh/a
Average gas production			65 Nm^3/h
Peak gas production			90 Nm^3/h
Lower heating value of biogas			22.55 MJ/Nm^3
Average gas composition			
CH_4			63 % (mole)
Noncombustibles (mostly CO_2)			37 % (mole)
Power system specific data			
Efficiencies		Full load	Part load
SOFC	$\eta_{el,SOFC}$	50 %	50 %
	$\eta_{th,SOFC}$	40 %	40 %
CHP	$\eta_{el,CHP}$	35 %	29 %
	$\eta_{th,CHP}$	48 %	58 %
System availability			
SOFC			8300 h/a
CHP			8000 h/a

A summarized overview of the economic and system models used for the economic assessment is shown in Table 3.

4 Results

Different analyses are conducted using the model developed above. Using the base case as a starting point, sensitivity studies are used to identify the most important parameters. Based on the results, the economic viability of an SOFC solution for biogas utilization is discussed.

4.1 Base Case

The *NPC* for the conventional CHP and innovative SOFC solution are calculated. The findings are summarized in Table 4. It can be readily seen that under the given assumptions and without regard to external factors, the installation of a CHP system is the best investment decision. The CHP system is

Table 4. Results of NPC calculation for the SOFC and CHP system considering the base case and potential subsidies. All values are given in million EUR.

	Scenario 1 – Average		Scenario 2 – Peak		Scenario 3 – Peak NG	
System	Base Case	w/ Subsidies	Base Case	w/ Subsidies	Base Case	w/ Subsidies
CHP	3.59	2.78	3.79	3.12	3.42	2.28
SOFC	5.26	3.69	6.26	4.69	5.82	3.65

NPC for a mere grid and boiler solution based on running costs: 4,160,000 EUR

better than the grid and boiler solution. In contrast, the SOFC system, with respect to its innovative character, has the highest *NPC*.

The particular high *TCI* of the SOFC system outweigh the benefit of its higher efficiency. This is shown in the given scenarios. It is obvious that the higher design capacity of Scenario 2 represents an overengineering and overinvestment. Even the use of additional capacity in Scenario 3 does not favor the SOFC solution, implying that the costs for the additional installed capacity overcompensate the benefit of an increased power and heat production.

Conclusively, assumed specific cost of 10,000 EUR/kW_{el} are not compatible in monetary terms in this market under the given assumptions. Analyzing the results of the base case, the effect of subsidies on the *NPC* in comparison to the base case is shown in Table 4.

In general, granted subsidies for cogeneration decrease the *NPC* of both power systems. Particularly, the fuel cell system benefits from the subsidies and the difference in *NPC* is reduced. In this case the SOFC system becomes more economical than a mere grid and boiler solution.

4.2 Sensitivity Analysis

The base case provides an answer to the question which solution is economically feasible for biogas utilization in sewage treatment plants. In order to estimate the validity of the base case figures, a parametric study concerning SOFC system cost, economic parameters and cost of electricity is conducted. Using a derived best and worst case scenario finally determines the range of economic viability for the SOFC solution.

Considering the results so far, the *TCI* of the SOFC system is the main parameter affecting the investment decision. By calculating the *NPC* of an SOFC system for a varying *TCI*, it can be determined at which point the SOFC solution becomes cost competitive.

Figure 3 illustrates the change of the *NPC* of the SOFC system compared to the *NPC* of a CHP system for varying *TCI*. It is obvious that with a decreasing *TCI*, the SOFC solution becomes competitive. For Scenario 1, the point of equivalence is reached at a TCI_{SOFC} of approximately 3600 EUR/kW_{el}. For Scenario 2 the same state is reached at a TCI_{SOFC} of 3150 EUR/kW_{el}.

An SOFC solution would become cost competitive to the conventional CHP unit, without any additional subsidies, at a system price between 3150 to 3600 EUR/kW_{el}. Including the grant of subsidies for SOFC operation, this value is considerably higher, at approximately 6200 to 6500 EUR/kW_{el}. The difference between the SOFC system and the CHP system originate from their cost distribution, as it is shown in Table 5.

The *CAPEX* have the highest share of expenditures of the SOFC system. For the conventional CHP system, the main costs are related to additional cost of electricity bought from the grid while the *CAPEX* generally have only a small influence on the *NPC*. This illustrates the opposing trends of investment cost and efficiency for the selection of the appropriate solution.

Since the additional cost of electricity (*CoE*) has a higher influence on the *NPC* of the CHP than for the SOFC system, it is reasonable that the *CoE* are an important parameter. Similar reasoning applies to

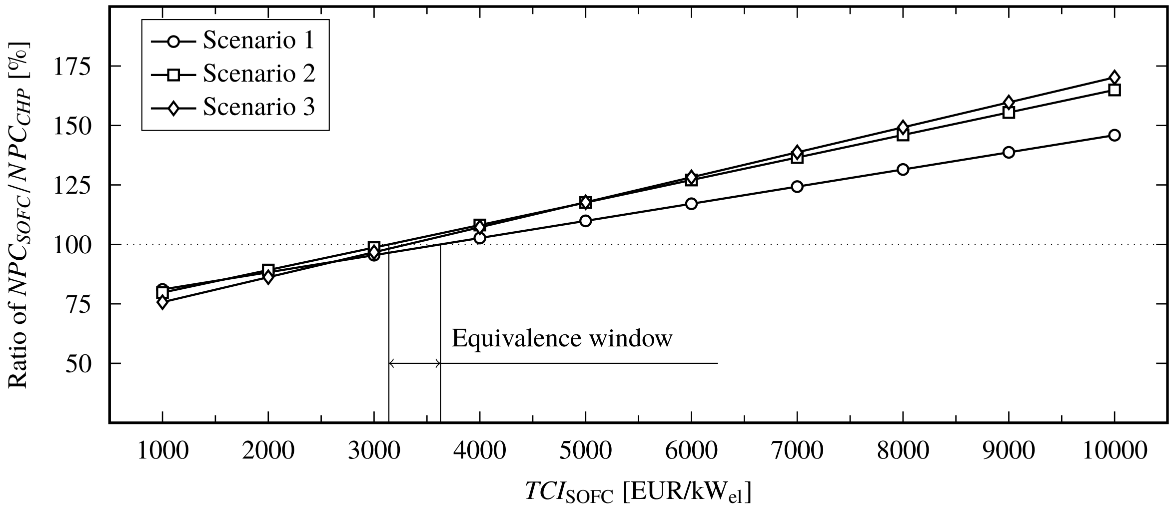

Fig. 3. NPC of a SOFC system compared to a CHP system for varying TCI_{SOFC}.

Table 5. Share of major cost compositions of NPC for the SOFC and CHP systems.

	Scenario 1		Scenario 2		Scenario 3	
Costs	SOFC	CHP	SOFC	CHP	SOFC	CHP
CAPEX	42 %	9 %	48 %	10 %	52 %	11 %
OPEX	11 %	4 %	13 %	4 %	24 %	22 %
CoE	37 %	74 %	31 %	77 %	19 %	60 %
CoH	10 %	12 %	8 %	9 %	6 %	7 %

the discount rate. High *OPEX* costs mean higher future cash flows and thus higher sensibility towards the discount rate. The same applies to a lesser extent to the price of natural gas as it is used to generate electricity and heat in Scenario 3.

The *NPC* of the SOFC solution in comparison to the CHP solution are prepared for different discount rates. The results for Scenario 1 are shown in Figure 4. Higher discount rates favor the conventional CHP solution while lower discount rates favor the SOFC solution.

A TCI_{SOFC} of approximately 4100 EUR/kW$_{\mathrm{el}}$ is already competitive for a 4 % discount rate in Scenario 1. In contrast, a 10 % discount rate lowers the TCI_{SOFC} to approximately 3200 EUR/kW$_{\mathrm{el}}$ for a plant operator to be indifferent between the two solutions. The same effect is noticed for Scenario 3. In this case, a change of the discount rate from 4 to 10 % requires a decrease in TCI_{SOFC} from 4000 EUR/kW$_{\mathrm{el}}$ to 2800 EUR/kW$_{\mathrm{el}}$ for economic equivalence of both technologies.

Another important influence derives from the additional cost of electricity as it is shown representatively in Figure 5 for Scenario 1. The impact of changes in the additional cost of electricity is notable. Regarding Scenario 1 the TCI_{SOFC} needs to be decreased from 4850 EUR/kW$_{\mathrm{el}}$ to 2550 EUR/kW$_{\mathrm{el}}$ in order to be equivalent to the CHP system. For Scenario 3, being the less favorable one for the SOFC solution, even lower TCI_{SOFC} have to be achieved. Therefore, higher electricity prices generally favor the SOFC solution as expected.

However, in Scenario 3 the price of natural gas becomes important as the additional design capacity is used to generate electricity and heat. Varying the natural gas price between 0.038 EUR/kWh and 0.058 EUR/kWh, a cost competitive SOFC system has a *TCI* between 2800 EUR/kW$_{\mathrm{el}}$ and 3900 EUR/kW$_{\mathrm{el}}$. However, as the sensitivity concerning the natural gas price is basically only affecting Scenario 3, it is not considered for the best and worst-case analysis. Putting the findings of the previous sensitivity studies together, a best and worst case variant provides a robust decision measure. The variant is calculated for Scenario 1 and 3 without taking subsidies into account.

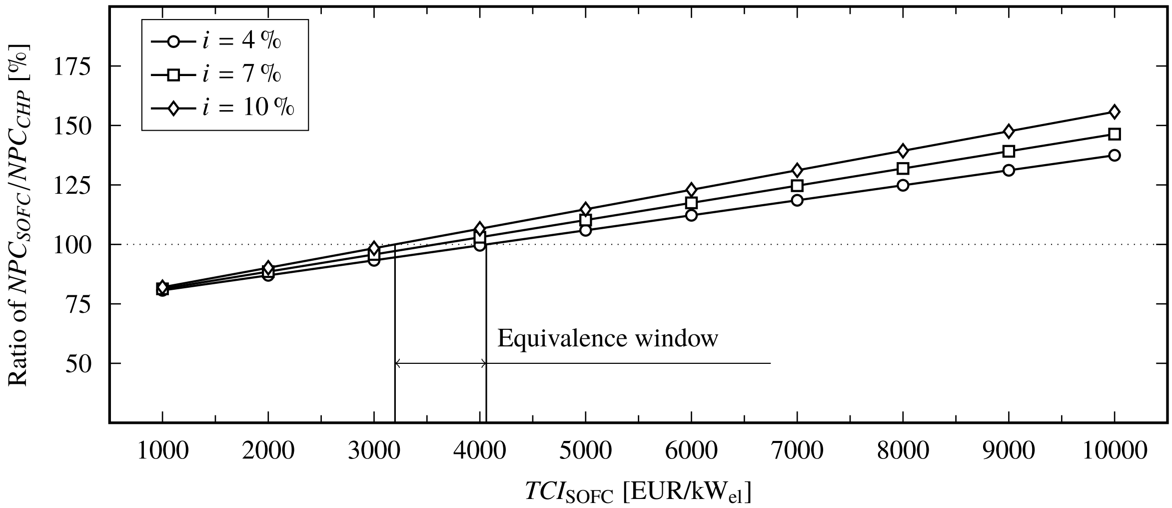

Fig. 4. Comparison of NPC of SOFC- to CHP-solution for Scenario 1 with varying TCI_{SOFC} regarding different discount rates and electricity prices.

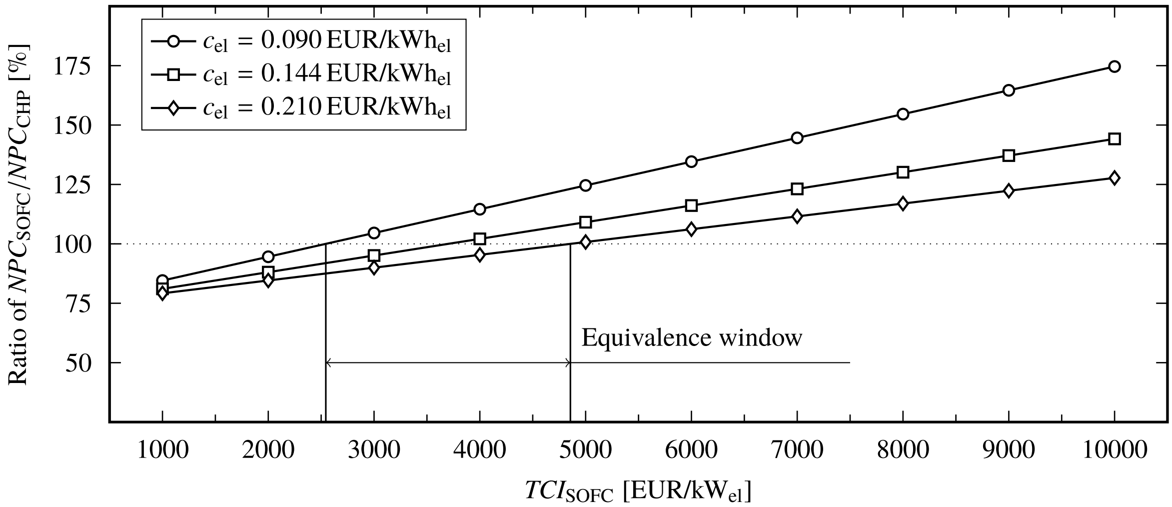

Fig. 5. Comparison of NPC of SOFC- to CHP-solution for Scenario 1 with varying TCI_{SOFC} and electricity prices.

- Assumptions for the best case: price of electricity = 0.21 EUR/kWh; Discount rate = 4 %
- Assumptions for the worst case: price of electricity = 0.09 EUR/kWh; Discount rate = 10 %

This study shows that the assumptions made have a very significant effect on the competitiveness of the SOFC system. The results vary by more than 100 % if the assumptions are either made in favor or against an SOFC solution. In the case of favorable assumptions for both scenarios, the SOFC system becomes competitive at a *TCI* of 5500 EUR/kW$_{el}$. Considering the worst case situation, an SOFC solution is competitive by a system cost of 2300 EUR/kW$_{el}$.

4.3 Discussion

The assessment has shown that an SOFC solution is a viable option for a sewage water treatment plant. However, is has to be concluded that specific SOFC system cost of 10000 EUR/kW$_{el}$ are unfavorable to date under the given assumptions.

Nonetheless, it has been pointed out, that with a cost reduction to 6500 EUR/kW$_{el}$, the SOFC system would close up the *NPC* of the SOFC and CHP solution, if subsidies are granted. Without subsidization, the SOFC system price would have to be reduced to somewhere between 3500 to 3800 EUR/kW$_{el}$ to become cost competitive to conventional CHP solutions.

However, the economic analysis has shown that the assumptions made have a strong impact on the obtained results. Furthermore, synergistic effects with other business units regarding heat and gas supply have been completely neglected, but can shift the investment decision in favor of a specific technology solution.

It has been shown that lower discount rates and higher electricity prices systematically favor the SOFC solution and vice versa. The statement to what extend the production cost of an SOFC system has to decrease in order to be cost competitive to a conventional CHP system vary significantly depending on whether the assumptions are made in favor of or against an SOFC solution.

5 Conclusion

A great potential for an SOFC solution is identified in the niche market of biogas utilization in sewage plants. However, the analyses have shown that the current specific SOFC system costs are still unfavorable in this market segment. Nonetheless, it is obvious that if subsidies or some initial incentives or sponsoring are available, the SOFC system closes up to the conventional CHP solution.

An SOFC system cost reduction is absolutely necessary. The economic feasibility in biogas utilization can be achieved at SOFC system cost of about 3500 EUR/kW$_{el}$ under general conditions. If subsidies are granted, the economic feasibility shifts to higher system cost. Considering that the SOFC system cost of 10000 EUR/kW$_{el}$ assumed in this assessment apply to a production volume of a few hundred modules a year only, the installation of one pilot plant of size would already double the output. If empirical effects of increased production are accounted for, such as the learning curve effect and economies of scale, then a major cost reduction occurs. Hence, a cost effective operation could be expected in near to midterm future.

Nomenclature

CHP	Combined heat and power
PAFC	Phosphoric acid fuel cell
SOFC	Solid oxide fuel cell

Mathematical symbols:

A	Annuities [EUR/a]
CAPEX	Capital expenditures [EUR]
CoE	Cost of additional electricity [EUR]
CoH	Cost of additional heat [EUR]
CRF	Capital recovery factor [–]
F	Cash flow [EUR/a]
LC	Labor cost [EUR/h]
NPV	Net present value [EUR]
NPC	Net present cost [EUR]
OMC	Operation and maintenance cost [EUR]
OPEX	Operational expenditures [EUR]
P	Electric Power [kW]
PV	Present value [EUR]
TCI	Total capital investment [EUR]
VAT	Value added tax [EUR]
c	Specific cost/price [EUR/kWh]
i	Interest rate [–]
n	Plant economic lifetime [–]

Greek symbols:

η	Efficiency

Subscripts and superscripts:

el	Electric
m	Maintenance
op	Operation
s+i	Service and inspection
th	Thermal

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