International Conference: September 15-17, 2008 Ragusa - Italy
"Innovation Technology to Empower Safety, Health and Welfare in Agriculture and Agro-food Systems"

Feasibility analysis of molten carbonate fuel cell – anaerobic digester power plant

Buccarella M., Cecchini M., Colantoni A.
Dept. Gemini, University of Tuscia, via San Camillo de Lellis – 01100 Viterbo, Italy, tel. +39 0761 357357, fax +39 0761 357453, e-mail: ergolab@unitus.it

Abstract

The problem of electrical energy generation is a controversial topic which from a long time has attracted and still attracts the interest of many different research sectors. Problematic topics such as scarcity of fossil fuels or high CO2 emissions directly related to worldwide energy consumption (estimated around 25000 million metric tons) lead to investigate new energy sources. In 2004, worldwide carbon dioxide emissions from energy consumption have been estimated around 25000 million metric tons (F.J. Friedrich et al. 1999). This huge amount of emitted carbon dioxide represents a strong threat for the environment and has pushed research efforts to the application of renewable energy sources.

These compositions present a remarkable amount of methane, thus the energy content of these gases is considerably interesting for energy recovery. Due to the large amount of fossil fuels employed for electricity and heat production, the use of biofuels is specially interesting for these applications.

Different technologies are currently available for combined production of electricity and heat. Even if internal combustion engines (I.C.E.) represent the most employed technology due to its high reliability widely demonstrated for decades, fuel cells is a very promising one.

Several system solutions have been proposed for integrating fuel-processing systems and MCFC (A. Moreno et al 2004) and the resulting performances are very high compared to traditional systems for energy conversion of biogas. The main goal of this work is focused on the production of electric power and heat through a MCFC system fed by biogas from anaerobic digestion. The main advantages of this system are:

- **Low environmental impact;**
- **High efficiency;**
- **Possibility of co-generation;**
- **Size flexibility;**
- **Replacement fossil fuels.**

Keywords: fuel cells, anaerobic digester, methane.

Introduction

Besides traditional approaches for the valorisation of biogas, the possibility of using biogas to run Molten Carbonate Fuel Cells (MCFC) for the production of combined heat and power (co-generation) is showing interesting results. The aim of this study is to assess the benefits and draw-backs of this energy system and to compare it with traditional biogas applications. Both technical and economical analysis of a real case-study are carried out. The selected case-study is a pig manure treatment plant located in Marsciano, near Perugia, Italy.

The performance of MCFC operating on biogas is assessed through experimental activities carried out at the Fuel Cell Group laboratory of the University of Perugia (Italy). Every test in which the MCFC has been run with biogas from an anaerobic digester, showed a highly satisfactory operation of the fuel cell. The economical analysis is based on the net present value (NPV) of an MCFC system and compared to an internal combustion engine system. Costs for the MCFC system are assumed to be equal to 1500 €/kW, 2000 €/kW and 3000 €/kW and it has been analyzed the difference between them.

Different cases with or without economic incentives and with or without co-generation have been studied. Green certificates (i.e. governmental incentives due to the low emissions) are also taken into account for NPV calculation (P. Lunghi et al 2001).

Material and methods

System description

The case study is a farm in Marsciano (Perugia, Italy) where pig manure is treated in two anaerobic digester to produce biogas which will be fed into a MCFC system. It serves different customers in a territory of 36 km^2. As shown in figure 1, this plant is composed of: 1) waste adduction section; 2) sewage storage: that minimize the fluctuation of incoming sewage; 3) two groups of pumps, used for sending the sewage to the digesters; 4) two primary anaerobic digesters, that can work in series or in parallel configuration; 5) one secondary anaerobic digester working for sedimentation and for collection of biogas; 6) sludge dehydration system (centrifuge); 7) cleaning treatment of biogas (desulphurisation); 8) aerobic stabilization; 9) compost system; 10) two internal combustion engine (ICE: 374 kW and 511 kW). The energy recovery section is currently represented by two I.C.E.s with nominal power of 370 kW and 510 kW. The aim of the present study is to demonstrate the feasibility to replace I.C.E.s with M.C.F.C. system. After the adduction section, there is an equalizer system to avoid flow fluctuations of incoming sewage. Sewage is then sent through two groups of pumps to the anaerobic digesters, two primary and one secondary. The two primary digesters may work in series or in parallel. The secondary anaerobic digester is used to increase the efficiency of biogas production and also acts as biogas storage system. The plant has the sludge treatment line and the biogas treatment line (desulphurisation of biogas) (A. Moreno et al 2004).

Use of Molten Carbonate Fuel Cell System

This work analyzes the use of MCFC system instead of ICE system. An internal report of Marsciano's plant (S.I.A. Engineering, 2003) shows that (in 2003) 2,16 million m^3 of biogas (chemical composition shown in table 1) have been produced. Taking into account the Low Heating Value (LHV) of biogas and the electric efficiency of the MCFC as 50%, the potential production of electrical power is 710 kW$_e$. Today, for ICE with an electric efficiency of 30%, the installed electrical power in the plant is 885 kW$_e$. MCFC system maximum power output can be calculated through the following relations:

$$W = B \cdot \frac{C}{100} \cdot L \cdot \frac{E}{100} \qquad \text{(a)}$$

where:
B = volumetric flow of biogas [m^3/h];
C = CH_4 in biogas composition [%];
L = LHV, Low Heating Value of CH_4 [kJ/m^3];
E = electric efficiency [%];
W = maximum power [kW].

The values of these parameters used in this case study are shown in table 1.

Table 1. Values used in case study

B [m^3/h]	C [%]	L [kJ/m^3]	E [%]	P [kW]
246,58	58	34535	50	713

Results

The chemical composition of the biogas from Marsciano plant after passing through a reforming process has been simulated in the lab. This composition is supplied and controlled by using a software. The chemical composition after reforming is shown in table 2.

Table 2. Chemical composition (%) after reforming

CHEMICAL SPECIES	REFORMING COMPOSITION
H_2	39.34
CO_2	18.97
CO	9.14
CH_4	0.27
H_2O	32.28
O_2	0
N_2	0

The tests have been executed on a single MCFC produced by Ansaldo Fuel Cells Spa. The test rig is composed of different parts as shown in figure 1.

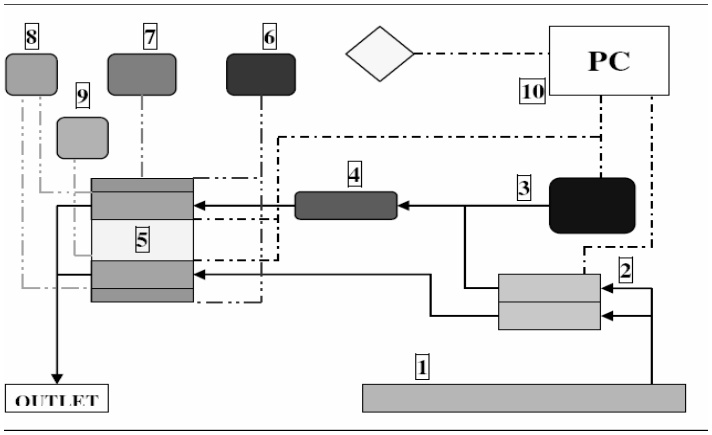

Figure 1. Outline of the laboratory: 1) Gas bottles box, 2) Digital mass flow meters, 3) Humidification system, 4) Heaters, 5) Single fuel cell, 6) Hotplate (temperature 650°C), 7) Pressure 4 bar, 8) Electric load, 9) Safety system, 10) Control system

An external box, containing different gas bottle, is connected to the lab. Inlet gas compositions are controlled by digital mass flow meters. The humidification system is fundamental to avoid carbon deposition (formation of solid carbon that could damage the FC).

Two hotplates increase the gas temperature, while the pressure system controls the pressure. The current for the polarization of FC is supplied by an electric load. The safety system is composed of sensors to detect leakages of H2, CO2 and others dangerous gases. The control system consists of a pc to control every part of the system and tests results. The first test generates the polarization curve, showing the variation of the fuel cell voltage in relation to the current density (b) for fixed inlet gas compositions. This polarization curve is shown in figure 2.

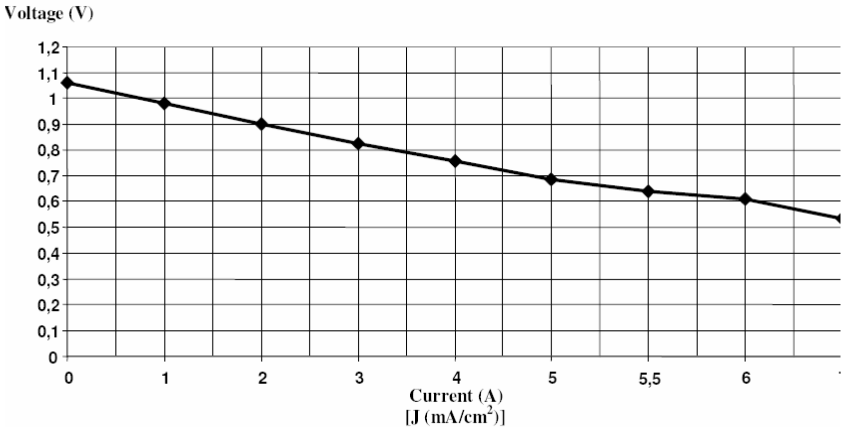

Figure 2. Polarization curve

The second test shows the voltage as a function of current density for a range of fuel utilization (c), shown in figure 3.

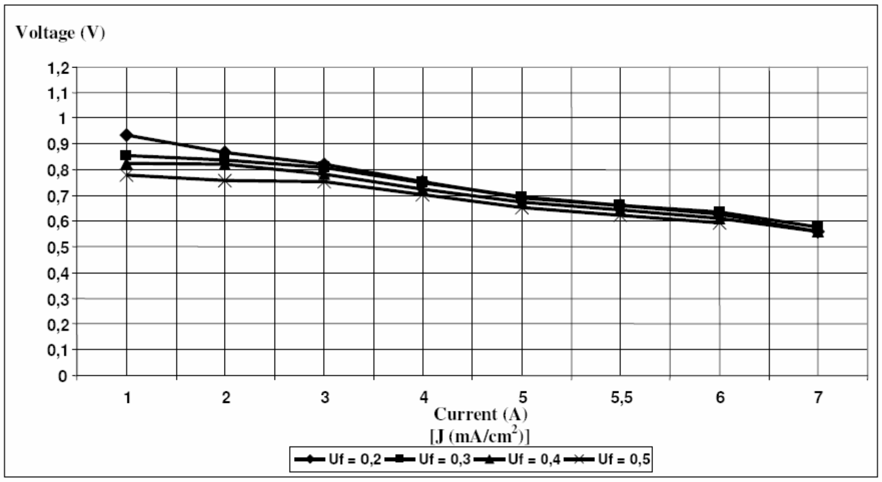

Figure 3. Voltage-Current - Uf

These curves show that biogas with these compositions is suitable for feeding fuel cells, after passing through clean-up process.

$$CurrentDensity = J = \frac{Current}{ActiveArea}\ [\mathrm{mA/cm^2}] \qquad \text{(b)}$$

$$FuelUtilization = U_f = \frac{FuelConsumed}{Fuel\,Provided} = \frac{e^-}{2(H_2+CO)} \qquad \text{(c)}$$

where:
e^- = electron flow [mole/s]
H_2 = inlet hydrogen flow [mole/s]
CO = inlet carbon monoxide flow [mole/s]

The aim of experimental tests was to assess the possibility of using this alternative gas under different values of relevant input parameters i.e. total current, current density, utilization factor (P. Lens et al 2005).

Economical analysis

The essential part of this work is the economical analysis described as the relation between the current use of ICE and the use of MCFC. This relationship has been established using NPV (Net Present Value, (d)) under two different scenarios, with and without economic incentives, with a sensitivity analysis assuming three different initial investments,1500 €/kW, 2000 €/kW, 3000 €/kW. Moreover, the relative importance of the cogeneration in both cases has been studied. After performing the technical analysis, the economical analysis using as term of comparison NPV is defined as:

$$NPV_n = -I_0 + \sum_{k=0}^{n} ACF_k \qquad \text{(d)} \qquad\qquad ACF_k = N_k \cdot \frac{1}{(1+i)^k} \qquad \text{(e)}$$

with:
I_0 = investment cost [€],
n = years.
i = discount rate,
N = cash flow [€/year],
ACF = Discounted Cash Flow [€/year],

The cash flow is the difference between the benefits (through the sale of the thermal and electrical power) and total cost (P + M):

$$N_k = R_k - (P_k + M_k) \qquad \text{(f)}$$

$$P_k = P_{k-1} \cdot (1+r) \qquad \text{(g)}$$

$$M_k = M_{k-1} \cdot (1+i) \qquad \text{(h)}$$

where:
R = benefits [€/year],
P = personal cost [€/year],
M = maintenance cost [€/year],
r = inflation rate.

Maintenance and personal costs aren't constants in the time, but in case study they are considered in relation of inflation and discount rates. In the case study the relation between the use of MCFC and present scenario (two ICEs) has been analyzed. In both cases, the possibility of co-generation has been considered. The goal of this analysis is highlighting the most relevant parameters for the insertion of MCFC in fuel cell's market (A. Moreno at al 2004). A software for macro and micro economical laws has been used.

Table 3. Economic real data

Disc. rate %	Infl. Rate %	Thermal energy cost €/kWh	Electrical power cost €/kWh	Maintenance cost (% of Initial Investment)	Personal cost €/year
5	2	0,057	0,182 (8 years) 0,0516 (after 8 years) 0,031 (without incentives)	10	3443

The economic real data shown in table 3 has been used. Figure 4 shows the evolution of NPV with time for both scenarios: future use of MCFC and present use of ICE.

In this figure, it is shown that the payback-time of MCFC system with initial investment of 1500 €/kW and 2000 €/kW is about one year, as ICE present system; the payback-time of MCFC system for initial investment of 3000 €/kW is about two years.

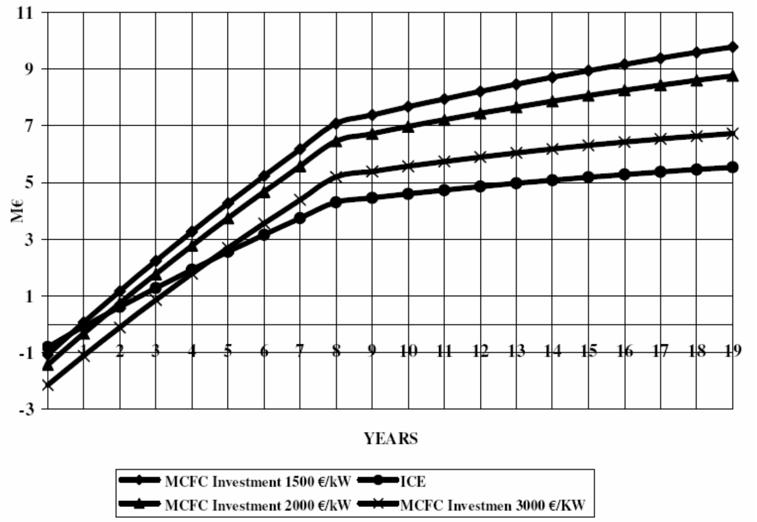

Figure 4. NPV with incentives and with co-generation

The slope of MCFC systems curves is the same or higher than the slope for ICE system curve. After the cross point of these curves, the higher slope of MCFC curves, the higher economical benefits for higher economical efficiency. In figure 5, the case without economical incentives is considered and it shows that the payback-time of CFC system with initial investment of 1500 €/kW and ICE system is the same, about two years; for MCFC system with initial investment of 2000 €/kW is four years and with initial investment of 3000 €/kW is twelve years. In figure 6, the case without co-generation and with economical incentives is considered showing the importance of cogeneration with different payback-time, between one and two years for MCFC system with initial investment 1500 €/kW, 2000 €/kW and for ICE system and of three years for initial investment of 3000 €/kW.

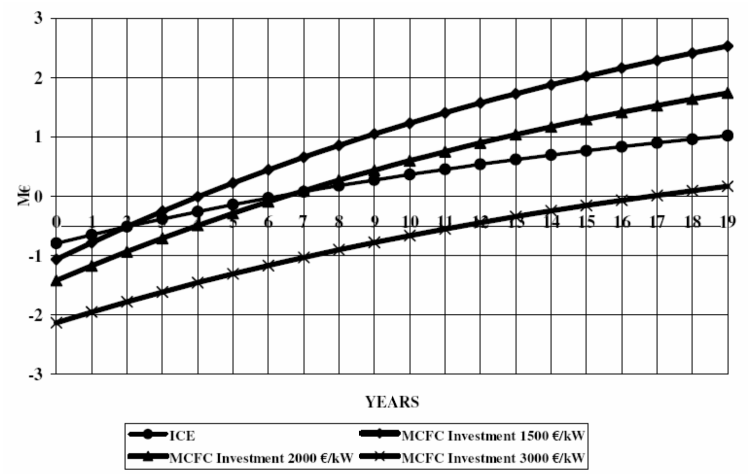

Figure 5. NPV without incentives and with co-generation

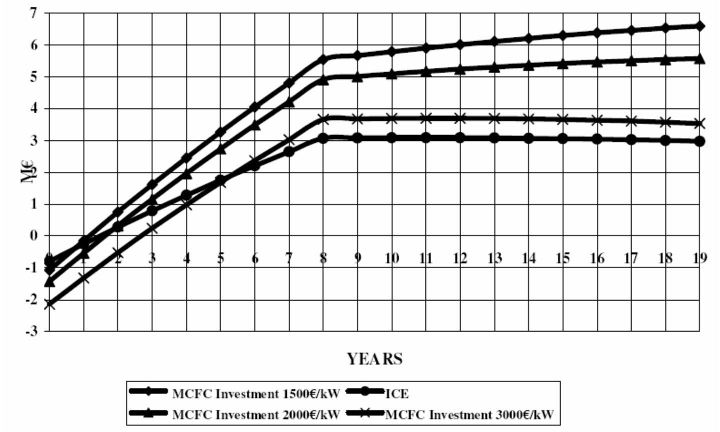

Figure 6. NPV with incentives and without co-generation

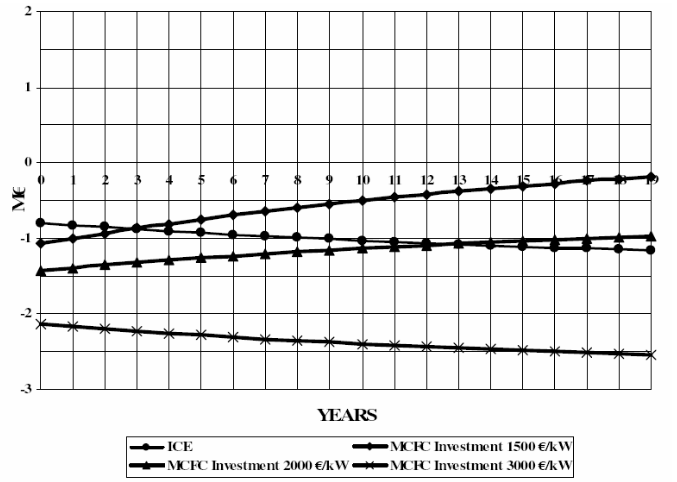

Figure 7. NPV without incentives and without co-generation

The case without co-generation and without economic incentives is not interesting because it has higher payback-times. It is shown in figure 7.

All these curves show that, with initial investment of 1500 €/kW, 2000 €/kW and 3000 €/kW, the use of MCFC is more economic than the ICE currently installed ICE. Moreover, economic incentives are very important, without them both configurations would have less advantages. Lastly, co-generation is essential for the economical and technical efficiency in both scenarios: use of ICE and use of MCFC system.

Conclusions

The conclusion of the study is that, although fuel cell systems diffusion is still limited due to the high manufacturing costs and the need of technology improvements, the possibility of integrating an anaerobic digester with an MCFC represents a potential business especially if the environmental benefits are translated into an economical saving. The tests carried out by Ansaldo dealing with single fuel cells, have been mainly focused on the use of biogas with low LHV (Low Heating Value) as biogas by anaerobic digestion. Their eventual use in MCFC involves a reduction of the emissions in atmosphere and higher electrical efficiency. In the last phase of the work, the economic analysis of the real case of Marsciano (Perugia) comparing new technologies (MCFC) to traditional ones (ICE) has been performed. This analysis, performed by using an Excel application, provides a number of diagrams that show the future possible use of fuel cell for thermal and electrical power production.

References

F.J. Friedrich, 1999, "The energy of the biomass", S.A.P.T. Technical Publication, S.L. (in Spanish).

P. Lens, P. Westermann, M. Haberbauer and A. Moreno, 2005, "Biofuels for Fuel Cells. Renewable energy from biomass fermentation", Integrated Environmental Technology Series, IWA Publishing, pp. 405.

P. Lunghi, R. Bove, E. Cerluini, A. Moreno, 2004, "Energy recovery from waste water treatment biogas: integration of an anaerobic digester with a high temperature biogas: integration of an anaerobic digester with a high temperature fuel cell", Proceedings of the second International Conference on Fuel Cell Science Engineering and Technology, Rochester, NY.

P. Lunghi, R. Burzacca, U. Desideri, 2001, "Fuel Cell and Gasification for the Trigeneration by Industrial waste: Criteria of Planning, Performances and Tests Case in Food Industry", Proceedings of the XXVII National Meeting ANIMP 2001, Spoleto (PG), Italy, (In Italian).

S.I.A. Engineering, "The purifier of Olmeto (Marsciano)", Marsciano Anaerobic Digester Plant, Internal Report, (in Italian) 2003.

The contribution to the programming and executing of this research must be equally divided by the authors.