Comparative analysis of different combined heat and power generation: fuel cells, gas turbine, internal combustion engine

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Abstract: - The paper presents the results of a detailed technical and economic analysis on the opportunity of implementing the fuel cells in distributed small scale cogeneration. The installations considered for the analysis were: gas turbine, internal combustion engine, Phosphoric Acid Fuel Cell and Melted Carbonate Fuel Cell. The power scale of the application was in the range of 0.1 – 1 MW for the electric energy generation. As the installations are used for combined heat and power generation the parameters considered for a complete analysis were: the electric efficiency, the thermal / electrical energy ratio, the fuel price, the equipment lifetime, the internal rate of return, the specific investment, the maintenance cost the annual operating time, etc. The results show that, for the current investment costs, the fuel cell cogeneration is still an expensive solution compared to conventional technologies. For an investment decrease with about 63%, reachable by state incentive or by technological development that will extend the fuel cell lifetime from 40000 to 80000 operating hours this solution becomes competitive to gas turbine or internal combustion engine for combined heat and power application.

Key-Words: - cogeneration, fuel cells, gas turbine, internal combustion engines

1 Introduction

The development strategies have as main targets the energy efficiency increase and to identify new energy resources (cutting edge energy sources) together with environment preservation.

In the last 30 years the European Community adopted laws for the environment preservation and pollution decrease by ecological quality norms. The legislation in the environment field for the European Community is the reference base for the member countries and represents an example of interstate collaboration.

The industrial and demographic development together with the ration between production and consumption involved an increase of raw materials consumption and therefore the rise of waste and pollutants.

Consequently, the present concerns in the field of energy generation and consumption are directed towards the implementation of „clean" technologies (higher efficiency and lower pollution).

The cogeneration, as solution for combined heat and power simultaneously generation, fits the „clean" technologies for energy generation characteristics due to its economic and environmental advantages.

Due to climate changes the main tasks imposed for the pollutants limitation were:

- The efficiency of the filtration installation increase and new technologies implementation;
- To improve the existing technologies or to change them with less polluting ones;
- To replace the conventional fuels "non-renewable and polluting" with renewable energy sources such as: solar, wind, biomass and hydrogen.

The hydrogen can be generated by numerous sources including renewable energy sources and by natural gas or liquid fuels (methanol) reforming process.

The technology that uses the hydrogen to generate electricity with high efficiency is the fuel cell. This technology has a large constructive variety and by its modular structure can be applied in different energy consumption sectors.

For medium and long terms it is expected that fuel cells will become an important factor on the energy market as alternative to classic low power cogeneration technologies based on gas turbine and internal combustion engine.

2 Theoretical approach

A fuel cell is a generator that converts the internal energy of a fuel directly into electricity using a controlled electro-chemical process. The theoretical

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conversion efficiency is high and the pollution is low. These arguments, generally accepted by the majority of scientific society, recommend the fuel cells as alternative especially to internal combustion engines (Otto and Diesel). It operates using the electro-chemical conversion. That consists in direct transformation of chemical energy contained in different active materials into electricity. This conversion type is called direct because there is no other energy type between the initial and final energy. The indirect energy conversion systems have several transformation stages including the thermal or mechanical energy. The direct energy conversion excludes the thermal or mechanical stage together with their transformation efficiencies leading to superior global conversion rates that do not depend on the limited efficiencies of internal combustion engine.

The concept to produce electricity from the direct conversion of chemical energy occurred when the idea evolved to generate electricity from, the reverse water electrolysis. The energy liberated by the conventional fuels oxidation and generally used as thermal energy can now be converted into electricity with very high efficiency. Due to electrons transfer between fuel and oxidant that occurs during most of oxidation reactions it is obvious that oxidation chemical energy can be converted directly into electricity.

The last decade proved the fezability of fuel cell in combined heat and power applications. For the moment there are operating about 200 installations, mainly PAFC type (Phosphoric Acid Fuel Cell). The operating temperature of these fuel cells type is 175 ºC and the heat recovery is performed in a temperature range of 80 to 120 ºC. The devices are connected to gas supply network having their own reforming and hydrogen generation installation together with the electric stations for the local networks connection [1].

The Phosphoric Acid Fuel Cell – PAFC use the phosphoric acid as electrolyte. Their conversion efficiency varies between 40 % and 80 %. The working temperature is between 150 and 200 °C. The existing PAFC can generate up to 200 kW, but there are also pilots able to generate electrical power about 1 MW. This fuel cell type has as main advantage the capacity to use hydrogen mixed to CO with a concentration up to 1.5 %. That enables the use of a large variety of primary conventional fuels and technologies to generate the hydrogen. If the fuel is used as combustible we need first to eliminate the sulphur. Among the drawbacks there are: the use of platinum as catalyst that increase the production costs, the low power and current intensity and high dimension and weight compared to other cells types.

At commercial level PAFC are most used; there are already existing tenths of installed MW in many cogeneration plants all over the world. Most of them are configured as cogeneration units connected to electricity networks.

Other fuel cell types adapted to cogeneration application are the proton exchange membrane (Proton Exchange Membrane Fuel Cell - PEMFC).

This type is the second as scale application due to relative simple fabrication process and to numerous implementation alternatives at this moment. PEMFC uses an electrolyte as a polymer membrane, thin and permeable. This membrane is small, light and functions at low temperature, approximately 80 °C compared to other electrolytes that require high temperatures up to 1000 °C [2]. To increase the reaction speed platinum is used as catalyst on both sides of membrane. In order to initiate the reaction the membrane has to allow the hydrogen protons migration but to exclude the pass of electrons and heavy gases. The efficiency of this fuel cell is about 40 – 50 per cent. At this moment there are prototypes capable of 50 kW power generation and other units of about 250 kW are at research centers as pilot devices [2].

Due to recent research results these cells reached good weight and volume characteristics (1 kg/kW and 1 dm^3/kW) compatible with the industrial application requirements, enabling the concept of cogeneration systems on a large scale, for individual or industrial use [3].

In [4], an energy, exergy and economic analysis of a fuel cell cogeneration system (FCCS) is presented. The FCCS is applied in a segment of the tertiary sector to show that it is a feasible alternative for rational decentralized energy production under Brazilian conditions. The technoeconomic analysis shows a global efficiency or fuel utilization efficiency of 86%. Analysis shows that the exergy losses in the fuel cell unit and the absorption refrigeration system are significant. The authors have used the same economic analysis with the same criteria (NPV, PBP, etc.).

In [5] the authors present a methodology for the study of a molten carbonate fuel co-generation system. The energy analysis shows high fuel utilization efficiency and the exergy analysis shows that the irreversibilities in the combustion chamber of the plant are significant. There has also been performed an economic analysis using different criteria.

In [6] the authors present some configurations of fuel cell cogeneration cycles and a study of the technical and economic feasibility for the installation of the cogeneration systems utilizing fuel cell\ connected to an absorption refrigeration system for a building of the tertiary sector\ subject to conditions in Brazil. The authors have used the same economic criteria to perform the analysis as we did.

The inconvenient of fuels cells application for cogeneration units is the low temperature of the recovered thermal energy, which has not quite mane possible users.

However, due to their undeniable technical advantages the fuel cells are a viable alternative to the existing modern cogeneration solutions at low and very low power level such as gas turbine and internal combustion engine.

3 Case study for the fuel cell application in cogeneration

According to previous data, the application domain for fuel cells is: 0.1 MW – 10 MW, meeting the requirements for electrical and thermal energy supply of different consumers as [7]:

- Small urban consumers;
- Industrial consumers;
- Commercial centers, hospitals, universities, airports, hotels.

3.1 Case analysis #1

There have been selected three different power levels and compared three available cogeneration technologies:

- 100 kWe;
- 500 kWe;
- 1 MWe.

The site conditions and hypotheses standing from the energy and economic points of view considered in the technical and economic analysis are listed in Table 1.

Table 1 The assumptions for comparative technical and economic analysis

Parameter	GT			TE			FC
Electric efficiency, %	24			37			42
Thermal/electric ratio	1.2/1			1.2/1			1.2/1
Fuel price, $/MWh	12			12			12
Analysis period, y	10			10			10
Internal rate of return, %	12			12			12
Installed capacity, MW	0.2	0.5	1	0.2	0.5	1	3000 $/kw
Specific investment, mil.$/MW	1.75	1.45	1.2-7	1.4-7	1.3-1	1.2-1	
Maintenance cost, $/kWh	0.0086			0.01305			0.0075
Operating hours, h/y	8000			8000			8000

Note: GT – Gas turbine cogeneration, TE – Internal combustion engine cogeneration, FC – Fuel cell cogeneration

During analysis the following steps were accomplished:

- Annual electricity and heat produced;
- Annual fuel consumption;
- The investments in the considered three variants;
- Annual fuel costs;
- Annual maintenance costs;
- Annual incomes;
- Net Present Value (NPV);
- Internal Rate of Return (IRR).

The interpretation of technical and economic analysis is based on calculated NPV and IRR. The results are presented in the Table 2.

Table 2 The results of comparative analysis

Solution	GT		TE		FC	
	NPV	IRR	NPV	IRR	NPV	IRR
	$	%	$	%	$	%
0.1 MW	-49099	6.65	-6766	11.04	-340063	-
0.5 MW	-11567	9.16	**54695**	**13.69**	-1700316	-
1 MW	-6242	11.11	**239227**	**15.96**	-3400633	-

The optimum solution for the considered power levels and site conditions is the internal combustion engine cogeneration plant if the required power exceeds 0.5 MW, when NPV is positive and IRR is bigger then a=0.12. For the other solutions the economic efficiency conditions are not fulfilled.

For the fuel cell solution the NPV is strong negative and IRR can not be defined. At lower power levels the NPV negative values accentuate. The computation was made for an optimistic version, considering that the investment of 4000 $/kW in one FC – PAFC, has a state incentive of 1000 $/kW (as in USA, to stimulate the new technologies development), decreasing the specific investment to 3000 $/kW.

For the GT and TE, due to specific investment decrease at power level increase, the economic efficiency of these solutions ameliorates for superior power levels.

To highlight the effect of lifetime increase together with the decrease of specific investment there has been performed a sensitivity analysis for these two parameters variation.

The assumptions made for this sensitivity analysis were:

- Installed power - 0.1 MW;
- Specific investment - 3000 $/kW;
- Lifetime period - 40000 hours;
- Fuel price - 12 $/MWh;
- Electricity price – 60 $/MWh;
- Heat price – 20 $/MWh.

The results of analysis are presented in the Fig. 1 and 2.

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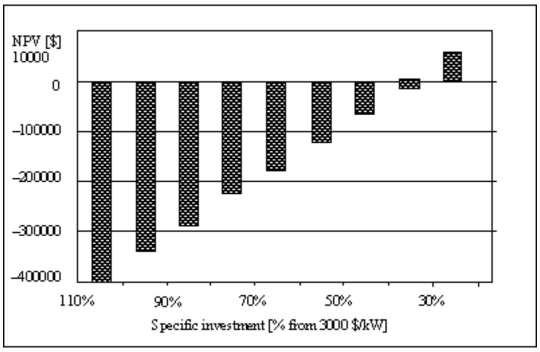

Note: 100 % represents 3000$/kW for a lifetime period of 40000 hours.
Fig. 1 NPV variation with specific investment

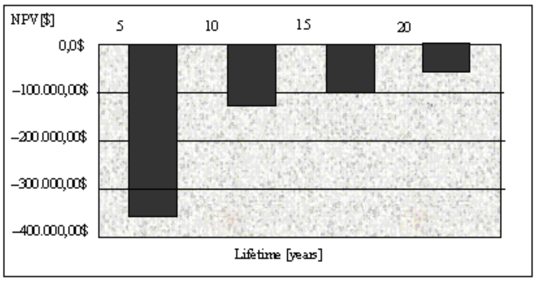

Fig. 2 NPV variation with lifetime period

The results of sensitivity analysis can be summarized in following main ideas:

- For a lifetime period of 40000 hours of operation NPV becomes positive only for the investment cost reduction with about 60 – 65 %;
- The investment decrease at approximately 1500 $/kW together with lifetime extension to 80000 hours, generate NPV that make the fuel cells competitive on the cogeneration market.

3.2 Case analysis #2

The comparative analyzed solutions are:

- Fuel cells type MCFC where the electrolyte is made of thin layer of melted carbonate. The material is a mixture of 62 % lithium carbonate and 38 % potassium carbonate. The melting point is around 650 ºC. The energy characteristics of this fuel cell are presented in Table 3 [8].

Table 3 The MCFC characteristics

Parameter	Unit	Value
Electric power	kW	250
Thermal powe	kW	180
Electric efficie	%	52
Global efficier	%	86

- Internal combustion engine – using on natural gas, with a heat recovery about 60 % from the thermal energy of flue gases and 40 % from the thermal energy of the cooling system.

The characteristics of the engine are listed in the Table 4.

Table 4 The TE characteristics

Parameter	Unit	Value
Electric power	kW	250
Electric efficiency	%	37
Global efficiency	%	63
Base cogeneration factor	%	82
Cogeneration factor	%	30
Thermal power (cogen)	kW	320
Recovery factor	%	78

The urban consumer profile supplied by the above mentioned installations are synthesized in Table 5.

Table 5 Urban consumer characteristics

Energy	Unit	Value
Electricity	kW	250
Heat	kW	1000
Heating	kW	800
Warm water	kW	200
Heating period	d/y	202
Warm water period	h/y	8000

The performed technical and economic analysis based on the economic data is presented in Table 6.

Table 6 Economic data accepted in the comparative analysis of TE and FC cogeneration solutions

Parameter		Unit	Value
Discount rate		%	12
Study period		Y	10
Fuel price (NG)		$/MWh	12
Electricity price		$/MWh	60
Heat price		$/MWh	20
Investment cost	FC	$/kW	4000
	TE	Mil $/MW	1.47
Maintenance cost	FC	$/kWh	0.0068
	TE	$/kWh	0.01305
Peak load specific Investment (Boiler)		$/MW	0.1
Maintenance cost of Boiler		$/MWh	$0.03*I_b$

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The analysis is also based on the NPV variation for the above mentioned conditions together with the following assumptions:

- The heat recovered from both solutions is residuary and results from the electricity generation process imposed by consumer;
- The lifetime period is the same for the compared solutions;
- Both electricity and heating are supplied by the cogeneration solutions.

4 Conclusion

The results enabled the following conclusions:

- The TE cogeneration solution for the considered specific investment in FC is economically more efficient;
- In the same conditions for an investment of 4000 $/kWh in FC, the NPV has a strong negative value (-6429000 $); NPV increases sensibly at specific investment decrease. The electricity price that rends the FC solution economical, NPV = 0, is 325$/kW;
- The solution efficiency is also influenced by variation of the other economic elements: operating time, maintenance costs, discount rate, electricity and heat prices.
- The element that decisively influences the fuel cell solution opportunity is the specific investment cost;
- The methodology used by authors has also been used in other published papers and the results are quite similar.

References:

[1] B. Linhoff, *User Guide on Process Integration for the Efficient Use of Energy*, Institution of Chemical Engineers, 1994

[2] C. Hewett, Policies for a Micropower Future, *Cogeneration and On-Site Production*, November-December 2001

[3] Gas de France, *Piles a combustibles industrielles*, Forum Energies, Paris 2001

[4] Jose Luiz Silveira, Elisangela Matins Leal and Luiz F. Ragonha Jr., Analysis of a molten carbonate fuel cell: cogeneration to produce electricity and cold water, *Energy* 26 (2001) pp. 891-904

[5] Elisangela Matins Leal and Jose Luiz Silveira, study of fuel cell co-generation systems applied to a diary industry, *Journal of Power Sources* 106 (2002) pp. 102-108

[6] J. L. Silveira and L. A. Gomes, Fuel cell cogeneration system: a case Of technoeconomic analysis, *Reneable and sustainable Energy Reviews*, 3 (1999) pp. 233-242

[7] J. Hirschenhofer, *Fuel Cell Handbook*, Forth Edition, Federal Energy Efficiency Technology Center, US Department of energy, 1998

[8] N.Q. Minh, T. Takahasi, *Science and Technology of Ceramic Fuel Cells*, Elsevier Science, Amsterdam, 1995