INITIAL STUDIES FOR THE INSTALLATION OF A SMALL SCALE SOFC SYSTEM OPERATING WITH LANDFILL GAS

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Abstract. *Fuel cells when considered under the objective of a profitable solution for the combined production of heat and electricity are in a pre-commercial situation. It is expected that in the next five years they manage to shown their profitability when compared with the traditional co-generation systems and that their position in the market can start to be important. This five year time delay can be shortened if the public awareness concerning the global warming effects, created by the energy conversion procedures, imposes the search of solutions able to solve nowadays environmental problems. In this paper the evaluation of available technical solutions concerning the use of a solid oxide fuel cell (SOFC) system working with landfill gas to produce an output 5 kW of electricity is discussed. The objective is to purchase and install a demonstration fuel cell plant in a landfill close to Oporto, in the northern region of Portugal, and to get experimental data from the system operation in real conditions. The necessary steps to fulfil such target are explained throughout the text.*

Keywords: *Fuel cell, solid oxide, landfill gas, electricity production.*

1. INTRODUCTION

The fuel cells as a practical solution for the production of electrical energy or the combined production of heat and electricity are in a pre-commercial phase. It is expected that in the next five years fuel cells can demonstrate their economic capability in comparison with traditional energy conversion systems and that market domination could develop afterwards as valid options for energy conversion systems. This five years delay time could be reduced, if public opinion pressure towards the solution of environmental problems created by global warming motivated by the continuous release of greenhouse gases raises and demands urgent solutions concerning the reduction of atmospheric CO_2 emission per unit of consumed energy. Such situation can lead to the penalization of energy forms based upon fossil fuel sources, and increase the publication of legislation to enhance the support of other energetic solutions more convenient to reduce the emissions of carbon dioxide, like for example fuel cells.

Nowadays there are several demonstration projects going on around the world using different fuel types as well as different fuel cell types. One of such combinations that deserves to be evaluated is a solid oxide fuel cell working with biogas or sanitary landfill gas (Abe et al., 2002). Fuel cells are an emergent energy conversion technology that may allow a clean and efficient use of the available energy found in biogas, although there are practical problems such us the variability of gas composition, which can be something difficult to handle by the cell. This variability is not only time dependent but also a function of the biogas source itself.

The biogas can be used to feed several types of fuel cells but the preference goes to high temperature fuel cells, namely the molten carbonate and the solid oxide versions (MCFC, SOFC), provide a previous cleaning of the feed gas can be implemented to wipe out sulphur and halogenated compounds. These high temperature cells are more tolerant to impurities and accept mixtures of $H_2/CO/CO_2$ as it is usually found in biogas or landfill gas (Ferreira, 2004).

As far as low temperature cells are concerned, like polymeric membrane or the phosphoric acid type, they can also handle biogas if in the amount of the cell a reforming process is applied to the gas with the subsequent removal of sulphur compounds, NH_3 and halogenated hydrocarbons. Besides the CO levels should be below 10 ppm (v/v).

There are presently some demonstration projects going on with fuel cells, using biogas or landfill and the results shown how technically feasible such approaches are. These projects employ different types of fuel cells and at the same time use biogas from different sources (Abe et al., 2002).

2. THE USE OF BIOGAS AS FUEL

2.1. Characterization of biogas. Different uses as fuel.

The biogas is a gaseous mixture of carbon dioxide and methane and it is produced in an anaerobic environment through the action of some bacteria on the organic material, which suffers a fermentation process under specific conditions of temperature, humidity and acidity. Methane is the main component, it is odourless and colourless, whereas other gaseous components of this mixture can provide a slight unpleasant smell.

In broad terms, biogas can be of two different origins, landfill gas or anaerobic digestion gas. This classification is in fact rather crude as the landfill gas is also the result of an anaerobic digestion process. The digestion gas can be produced during industrial waste water cleaning process, stabilization of waste mud, recycling of biowastes or agricultural wastes. It is a renewable source of energy and as such its used is becoming more and more common as a technique to assure a sustainable development and to reduce the use of fossil fuel sources. Besides being used in the combined production of heat and power, it can also be used as fuel for internal combustion engines, like in northern european countries, as fuels for fuel cells or even to be sent to the normal natural gas network after suffering a suitable cleaning treatment, Fig. (1). The main disadvantage concerning its utilisation is connected with the variability of composition, which is time and source dependent.

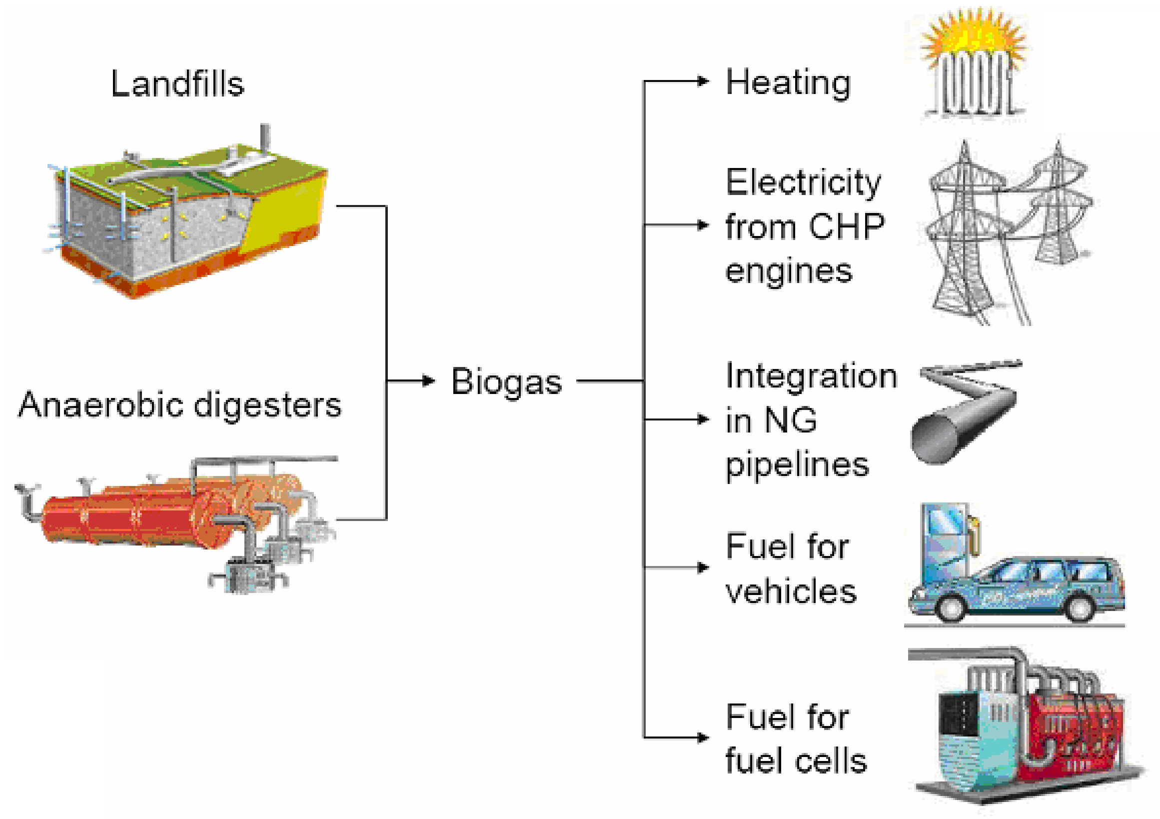

Figure 1 – The use of biogas as a renewable source of energy. (Ferreira, 2004)

According to the final use of biogas, the gas quality must be adjusted. Main components to remove are, H_2S, H_2O, halogenated hydrocarbons and CO_2. The removal of H_2S and halogenated hydrocarbons is necessary to avoid corrosion problems and also because at high concentrations the H_2S is toxic and also to avoid the formation of SO_2/SO_3 in burner systems. The removal of steam is necessary to avoid condensation concerns in gas pipelines and subsequent formation of acid solutions. The CO_2 is a diluting component which means a minor specific energy for the biogas.

2.2. Characterization of landfill biogas.

The sanitary landfill gas is obtained through the anaerobic digestion of organic wastes disposed in a landfill. Wastes are mechanically pressed and covered and after the anaerobic decomposition process the biogas is released. The gas is slowly released in the atmosphere leading to unpleasant smells, local air pollution and explosion risk. As the landfill gas has around 50 % (v/v) of methane its greenhouse effect is rather important in terms of global warming potential, (Spiegel et al., 1997).

However, methane, the main component of biogas and landfill gas has a high energy potential and should be collected and used as an energy source. The methane capture process is standardized and the Environment Protection Agency (EPA) has defined the methodology to be followed to control the emissions and collection of the landfill gas.

The rules are mainly concerned with the non-methane gaseous emissions (NMOC) concerning about a hundred different dangerous organic compounds and pollutants like for example vinyl chloride and benzene, which are released in the landfill gas. These noxious emissions are usually below 1 % (v/v) whereas methane corresponds to about 50 % (v/v), while the CO_2 volumetric percentage stays is in the 25-50 % interval (Spiegel et al., 1997). The calorific value of landfill gas is consequently around 50 % of the corresponding value for natural gas..

According to the above mentioned standards, landfills that release more than 55 L per year of NMOC must install a gas collecting system and a treatment system able to destroy 98% of NMOC or to reduce its emissions to less than 20 ppm (v/v). In this process, the greenhouse gas potential of the methane existing in the landfill gas is also eliminated and if conveniently accounted for, the energetic potential of the methane is profitably employed on heat or power production. This collection technology is well developed. The procedure consists on drilling vertical holes with 0.6 m diameter 15 to 92 meters apart. A perforated pipe is introduced into the holes and the pipe is filled with gravel. All the vertical buried pipes are connected with a main gas distributor pipe, from then to a lixiviate removal system and afterwards to a gas pump for distribution, Spiegel et al. (1997).

The collected gas can then be used for electricity or heat production and because some evaluations say that the landfill gas can fulfil around of 1 % of the USA energy demands, EPA is promoting the energy production through landfill gas under these grounds. Following this perspective the use of fuel cells is an emergent solution that can promote the clean, efficient and economic use of landfill gas energy, although there some problems still to solve. One of the main problems is precisely the molar composition variability of the landfill gas either as a function of time or as location of the collecting ground (Spiegel et al., 1997).

The use of biogas and its pre-treatment to be used as fuel for solid oxide fuel cells (SOFC) are characterized in the next section.

2.3. Biogas pre-treatment unit.

As biogas can be used in different types of fuel cells, according to the chosen type of cell different pre-treatment or reforming units should be adopted. The following table, Tab. (1), presents the tolerances of the several fuel cell types according to the type of gaseous component being referred.

Table 1 – Effect of different gaseous components in fuel cell types. (Ferreira, 2004)

	Types of fuel cells			
Component	PEMFC	PAFC	MCFC	SOFC
H2	Fuel	Fuel	Fuel	Fuel
CO	Noxious	Noxious	Fuel	Fuel
CH4	Inert	Inert	Fuel	Fuel
Ammonia	Noxious	Noxious	Fuel	Fuel
Sulphur	Noxious	Noxious	Noxious	Noxious
Halogenated	Noxious	Noxious	Noxious	Noxious

Looking at the data shown in Tab.(1), CO and ammonia are noxious components for proton exchange membrane fuel cells (PEMFC) and phosphoric acid fuel cells (PAFC), whereas they can be supplied for high temperature fuel cells like solid oxide fuel cells (SOFC) and molten carbonate fuel cells (MCFC). On the other hand methane can be directly used in MCFC’s and SOFC’s and is innocuous for PEMFC’s and PAFC’s. By means of external reformer, methane can however be decomposed in hydrogen which will be used as fuel for both cell types, PEMFC and PAFC.

According to what has been explained, different types of approaches must be adopted as far as biogas pre-treatment or decomposition is concerned, Fig. (2).

Through the analysis of Fig. (2) it can be seen that high temperature fuel cells (MCFC and SOFC) can be fed directly with biogas provide the gas suffers a pre-treatment procedure in order to remove halogenated hydrocarbons, sulphurous components and siloxanes. These fuel cells can operate with mixtures of $H_2/CO/CO_2$.

For low temperature fuel cell the pre-treatment of the biogas must follow more rigorous procedures, beyond those adopted for MCFC e SOFC. Now it is necessary to reform the gas and to assure CO levels below 10 ppm (v/v).

The main conclusion to be drawn from this simple analysis is that high temperature fuel cells like MCFC or SOFC are the most adequate to directly handle biogas, because of their main advantages (Ferreira, 2004):

- Higher tolerance to impurities;
- Higher efficiencies;
- Simpler gas pre-treatment units.

The biogas to be used as direct fuel for a high temperature fuel cell must then be free of sulphur, halogenated compounds and should be a mixture of methane, nitrogen, oxygen and carbon dioxide. Design specification for the pre-treatment unit should allow a maximum value of 3 ppm (v/v) of sulphur and also 3 ppm (v/v) of halogenated compounds and the unit exit. These low level contaminants will be cleaned by means of internal cleaning devices that normally exist inside the fuel cell systems.

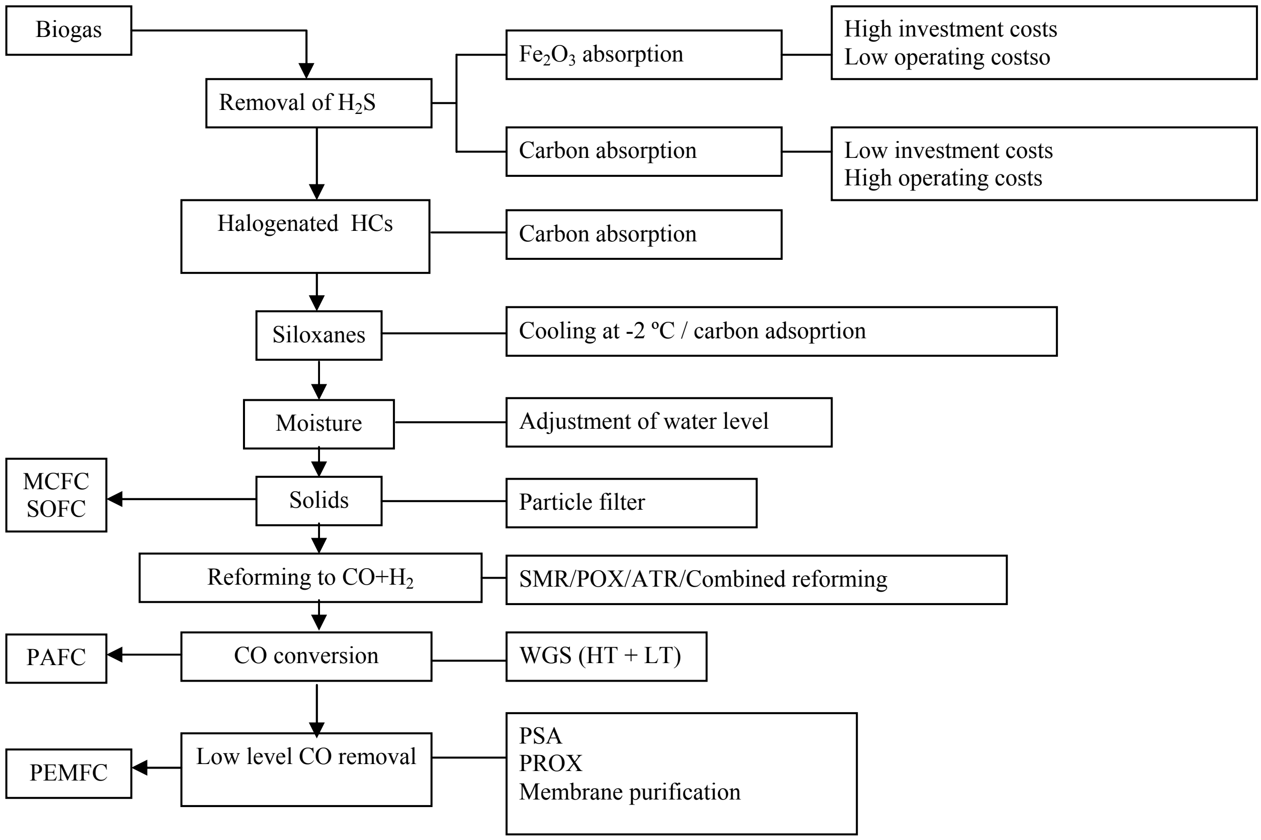

Figure 2 – Different steps in the pre-treatment of biogas. (Ferreira, 2004)

2.4. The use of biogas as fuel for solid oxide fuel cells.

High temperature fuel cells like SOFC can be used at high power demand situations in industrial environment or in central electricity generating plants. Some manufactures consider that SOFC could also be used in self propelled vehicles and are accordingly developing auxiliary power units (APU) using this type of cell. The main characteristics of the SOFC are presented in Tab. (2).

The choice of a SOFC is based on the following advantages, when compared with other fuel cell solutions:

- The high operating temperature (700-1000°C) allows the combined production of heat and power and at the same time no catalysts are required;
- The high working temperature allows the perfect thermal integration of all conversion and purification steps for the fuel and as a consequence a higher overall efficiency is achieved;
- Because SOFC's have higher efficiencies there is a significant reduction in air pollution and in the emission of greenhouse gases;
- SOFC's have a low degradation rate and keep an almost constant efficiency during their lifetime;
- These cells present a high efficiency even when working at partial loads;
- Solid oxide fuel cells accept a wide range of fuels like for example methane, coal gas, biogas, hydrocarbons and of course hydrogen. The cell flexibility opens a hole range of operating possibilities for any costumer.

Table 2 – Main characteristics of SOFC

Electrolyte	Solid-oxide
Operating temperature	600 – 1000 ºC
Reformer	External/Internal
Oxidant	O_2 / Air
Efficiency (without cogeneration)	45 – 60%
Maximum efficiency	85%
Maximum power	220 kW
Use of produced heat	Water heating or steam generation

The biogas is then an interesting fuel to be used in SOFC's because of the advantages of such approach like the use of a waste heat for energy production and the reduction or even the avoidance of greenhouse gases emissions.

The composition of the biogas produced by means of anaerobic digestion of biological wastes, although variable in time, is in medium terms of the order of: CH_4 = 50-70%, CO_2 = 25-50%, H_2 = 1-5% e N_2 = 0.3-3% (v/v), besides some minor impurities, namely NH_3 and H_2S (Hammad et al., 1999; Van Herle et al., 2004). Hydrogen, carbon monoxide or mixtures of H_2+CO, obtained through methane reforming can also be used as fuel for high temperature fuel cells like

SOFC's to produce electricity and heat (Vayenas et al., 1997; Stoukides, 2000). Fuel cells can use methane as fuel provide external reforming of this gas takes place ahead of the cell and a mixture of CO and H_2, is supplied to the cell.

Alternatively a more attractive and advantageous solution is to go for internal reforming. In this situation fuel reforming takes place inside the cell, in the anode, thus avoiding the use of an external reformer.

The kinetics of the reforming reaction of methane as well as of the oxidations of H_2 and CO are very fast at normal operating temperature of SOFC's. Besides, the reforming reaction is endothermic which can generate a severe anode cooling effect which can present an adverse impact upon the cell performance. However this situation can be compensated by means of adequate use of the heat released at the parallel oxidations of H_2 and CO.

Yentekakis (2006) carried out studies to find out the possibility of operating SOFC's directly with biogas (CH_4 +CO_2). He used a solid electrolyte, GDC (cerium oxide stabilized with gadolinium) and the following electrode materials, GDC in the anode and La0.54Sr0.46MnO_3 in the cathode. Gold was used as anode component in order to inhibit carbon deposition. The experiments showed that the addition of Au to the Ni electrode promotes the prompt oxidation of carbon by O_2 or O^{2-} (Besenbacher, 1998), avoiding any negative influence on the cell performance.

Impurities containing sulphur can also deactivate the majority of catalysts used for methane reforming, as well as the cell anode, requiring the previous treatment of the biogas. Ammonia is not problematic for SOFC's, being easily oxidized to N_2 and H_2O.

Presently several demonstration projects are under way using different fuel cells types operating with different fuels, (Abe et al., 2002), Tab. (3) According to public reports, demonstration projects of fuel cells working with natural gas have high efficiency and durability. A demonstration project of a 25 kW SOFC in Japan has until now 13,000 operating hours and more than 90% availability; a 100 kW demonstration Project in Holand has shown an efficiency of 42% while another system composed by 250 kWe fuel cell and a 50 kWe micro-turbine (Siemens-Whestinghouse) has an efficiency of 60%, Fig. (3). The SOFC's have shown, when fed with biogas, higher efficiency and lower sensitivity to gas impurities.

Figure 3 – Siemens-Whestinghouse demonstration project in Germany.

Another example is the use of biogas as fuel of a small module of SOFC in the "Maison Blanche" farm in Lully, Switzerland. This farm has been using, for the last nine years, biogas from domestic animals and recently a module Sulzer HEXIS SOFC (1 kW) (Van Herle, 2002) was installed with demonstration and research purposes. Also in Switzerland, a SOFC, working with biogas is being tested producing electricity for domestic use, (Schuler, 2001). A demonstration at Cannock landfill in Great Britain validated the feasibility of utilizing a SOFC with landfill gas. The fuel cell ran at 18.5% efficiency for a five hour period (Abe et al., 2002).

Presently a new project, named "BioSOFC – Life program" is starting promoted by a spanish company from Astúrias (BIOGAS FUEL CELL, S.A.). The objectives of this project are to design, built and erect a system composed by a fuel treatment unit and a SOFC with 5 kW electrical output. This system to be installed in several landfills will be fed by the released biogas and its behaviour will be monitored.

Table 3 – SOFC demonstration projects under way

Year	Client	Electric power (kWe)	Cell type	Stack length (mm)	Number of cells	Operating hours (h)	Fuel
1986	TVA	0.4	TK-PST	300	24	1760	H_2/CO
1987	Osaka Gas	3	TK-PST	360	144	3012	H_2/CO
1987	Osaka Gas	3	TK-PST	360	144	3683	H_2/CO
1987	Tokyo Gas	3	TK-PST	360	144	4882	H_2/CO
1992	JGU-1	20	TN-PST	500	576	817	NG
1992	UTILITIES-A	20	TN-PST	500	576	2601	NG
1992	UTILITIES-B1	20	TN-PST	500	576	1579	NG
1993	UTILITIES-B2	20	TN-PST	500	576	7064	NG
1994	SCE-1	20	TN-PST	500	576	6015	NG
1995	SCE-2	27	AES	500	576	5582	NG
1995	JGU-2	25	AES	500	576	13194	NG
1998	SCE-2/NFCRC	27	AES	500	576	13000+	NG
1998	EDB/ELSAM	100	AES	1500	1152	4035+	NG
1999 2001	EDB/ELSAM/ RWE	100	AES	1500	1152	12653 3701+	NG
2000	SCE	220	AES	1500	1152	1522+	NG
2002	OPG	250	AES	1500	2304	1200+	NG
2002	FCT/RWE	5	AES			3100	NG
2003	FCT/UAF	5	AES			2200	v
2003	FCT/JFW	5	AES			1600	NG
2003	FCT Ford	5	AES			850	

3. CHARACTERISTICS OF THE DEMONSTRATION PROJECT UNDER WAY.

In Portugal an applied research and development project named “EDEN – Endogeneizar o Desenvolvimento de Energias Novas” and financed by the Portuguese government intends, among other tasks to be performed, to start a technology transfer process through the installation of a high temperature fuel cell system operating with sanitary landfill gas and producing thermal and electrical power. The system will be installed in the Oporto region, in the north of Portugal and talks are under way with local authorities to find out a suitable landfill site for the system location. The system should have around 5 kW of electrical output. The main objective of this action, besides its demonstration purposes, is to gain access to a new technology as well as obtaining technical formation for people in high temperature fuel cells.

A consortium was created among private companies, universities and R & D institutes to lead the EDEN project and the intention of this consortium is to get acquainted with the capacities and limitations of this energy conversion technology, the SOFC’s, for further application in larger and more frequent distributed generation premises.

The use of landfill gas as fuel for the SOFC system was considered fundamental for the future success of the demonstration. Cooperation among consortium partners and equipment suppliers is most desirable and has been one of the key parameters for evaluation of technical proposals. Contacts are under way with “BioSOFC – Life program” who were kindly helping the team in charge of the EDEN project.

A simplified operating scheme of the system to be installed is shown on the next figure, Fig. (4).

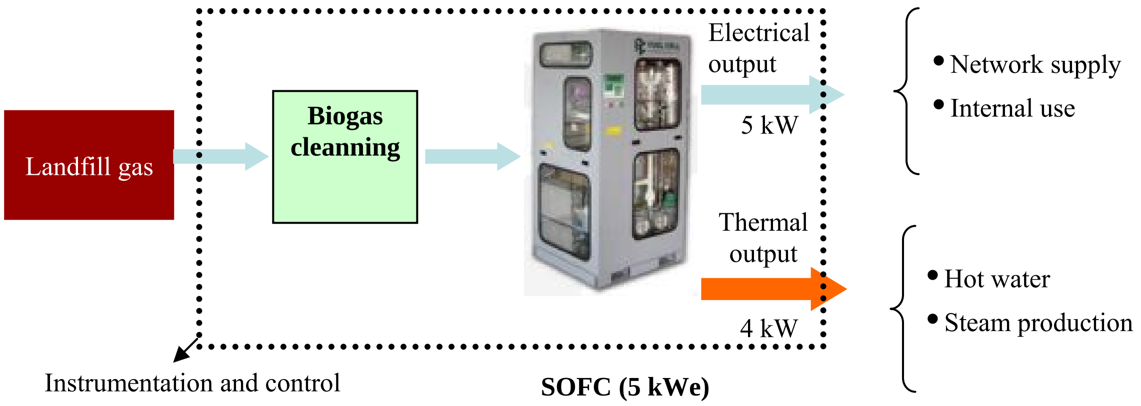

Figure 4 – Simplified installation system to be adopted for the demonstration project.

3.1. Biogas cleaning unit.

The first step of this demonstration project is the design of a landfill gas pre-treatment unit to get a free contaminant gas at the entrance of the fuel cell.

In fact the process design of the landfill gas pre-treatment unit and cleaning process is dictated by the final gas purity requirements for the fuel cell, the composition of the incoming landfill gas and its complex mixture of trace contaminants, and the requirement that the gas cleanup process is capable of handling variations of inlet-gas composition. The fuel cell gas quality must be essentially free of all S and halogen contaminants and consist primarily of a mixture of methane, NO_2, O_2, and CO_2. The current design specification allows a maximum exit S level of 3 ppm (v/v) and a maximum halogen level of 3 ppm (v/v). The siloxanes components must also be eliminated. Those levels can be successfully removed by an activated carbon bed (being currently projected) which is maintained at a constant low temperature and humidity to ensure consistent high-trace contamination removal.

3.2. Fuel cell.

The adopted choice for the present demonstration project was a solid oxide fuel cell with parallel utilization of the electricity and thermal output of the cell. The reasons that supported this choice were presented in section 2.3 of this communication.

Following a thorough analysis of manufactures data and commercial conditions it was chosen a 5 kWe from Acumentrics, Fig. (5), whose characteristics are shown next.

Figure 5 - SOFC (5kWe) system from Acumentrics.

System description of Acumentrics SOFC (5 kWe):

Gas supply	0,84 m3/h (SPT). NG (8.5 kW)	
Electric power	DC	3.5k W
	AC	3 kW (not grid connected)
Heat recovery	3 kW	
Efficiency	**Electrical**	34%
	Overall	70%

Technology	**Stack**	Acumentrics (tubular, non pressurized, POX - parcial oxidation reforming without recirculation);
State of art		Product development;
Future market		UPS, power generation, residential military (several kW).

Advantages:

- Large experience;
- Inherent strength and tolerance to rapid temperature change;
- Lowest cost per kW;
- System development for system up to MW;
- POX reforming without recirculation, no operating problems with the high CO_2 in the form of carbon (Steam reforming and recirculation option for the end of this year):
- Inverter and other parts of the BOP were also developed by Acumentrics.

Disadvantages:

- Maintenance; training for client. Replacement of the stack, only technician from US.

Experience with SOFC systems:

- 31 units delivered to the field, 16 for 2007;
- Field demonstrations operating now for over 3,000 hours (cells proven at 14,000 hours).

Experience with biogas:

- Some experience in operating on biogas. Some adjustments can be made to run the system on a fuel different from natural gas.

3.3. Instrumentation and control.

Besides the gas cleaning unit and the solid oxide fuel cell a measurement and control system will be installed to verify online the cell performance, specially its dependence upon composition variations of the landfill gas. Alarm and intervention systems are also being developed to guarantee the required safety operating conditions.

4. CONCLUSIONS.

Solid oxide fuel cells can then be fed with pure H_2 as well as with methane, methanol and ethanol. Biogas can also be used as fuel. A particular case of biogas is the sanitary landfill gas. However in this last situation care must be taken to assure the complete removal of impurities from the gas.

The use of a landfill gas pre-treatment unit, is then required, to avoid cell contamination mainly through sulphur based components.

According to several authors, through the utilization of a proper cleaning installation it is then possible to directly use the landfill gas in the fuel cell, provide the cell has the right catalyst and anode adapted for methane. The main remaining problem will then be the composition variability of the landfill gas which is a technological limitation difficult to handle.

In the present paper it was presented a brief description of the main steps taken for the installation of a SOFC plant using directly biogas from a sanitary landfill situated in the north of Portugal.

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