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Non conventional fuels for Molten Carbonate Fuel Cells: from niche market to commercialization

Introduction

It is clear that the current energy infrastructure in Europe is a precarious one: increasing energy density of the consumption pattern, strongly oscillating barrel prices, persistent disputes about the viability of nuclear power, continuing dependency on overseas fuel imports and being at the mercy of volatile governments and organisations, growing environmental concern and very practical directives and deadlines to be met, are all elements that are putting the way we think about and organize our energy supply under pressure. Also on the demand side severe corrections have to be undertaken: product and associated waste flows have to be interpreted differently, efficiency and sustainability becoming key issues. In addition, there is a huge challenge to provide an everyday product (energy) – that is taken absolutely for granted – in a radically different, difficult, but fundamentally improved way at accustomed and competitive cost.

One of the most immediate, and effective, ways to tackle this challenge is to minimize losses and waste by maximizing the exploitation efficiency of the resources that are utilised. Fuels from waste or biomass, by nature of their transient origins, are generally poor in energy content, which imposes localized deployment and maximum efficiency in their utilization in order to obtain a useful amount of work and/or heat. The use of these sources however, is crucial to decrease dependence on fossil fuels and to increase the security and sustainability of energy supply.

Their conversion into useful energy does not upset the balance of the planet's atmosphere to a significant extent: on condition of a sustainable method of production, renewable, non-conventional fuels are clean, compatible with the Earth's natural habitat, and CO_2 neutral.

In the effort to maximize the energetic yield from alternative energy sources like biomass, sewage sludge, manure, waste flows from the food and agriculture industries, and wanting to minimize environmental impact in terms of polluting emissions, the coupling of molten carbonate fuel cells (MCFCs) to the fuel gas produced from these sources is an attractive option.

In this article, this concept will be elaborated and the key points of the system principle and integration issues will be set out. A review is offered of two important methods of production of alternative fuels (anaerobic digestion and gasification) and the feasibility of their conversion to electricity and heat by a MCFC appliance. The principles of the two fuel production technologies and the characteristics of the alternative fuel produced will be described, especially in relation to their successive implementation in a MCFC. Technical barriers in this coupling will be indicated and possible solutions will be highlighted.

System principle

Current potential for implementation of clean, high-efficiency, electrochemical conversion of fuel favours high-temperature fuel cells in particular, owing to their capability to operate relatively easily on hydrocarbon-based fuels, rather than relying on pure hydrogen as is the case for low-temperature fuel cells.

The coupling of MCFCs to non conventional fuels has potentially enormous benefits, in terms of highly efficient energy use and low environmental impact, in line with a sustainable concept of energy supply: the modular build-up of MCFCs makes them adamantly suitable to a decentralized energy infrastructure, which relieves dependencies on primary energy carrier imports and encourages local productivity.

MCFCs could thus operate on such different fuels as biogas from anaerobic digestion of sewage sludge, organic waste or dedicated biomass, landfill gas, syngas from a thermal gasification or pyrolysis process using biomass or waste material, Refuse-Derived Fuels (RDF), industrial

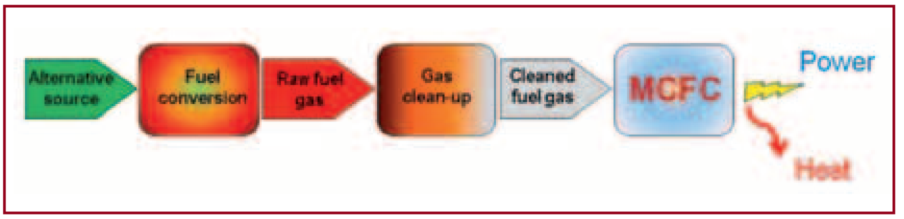

Figure 1. Principle of conversion of a generic Alternative Source to electricity and heat using a high-temperature fuel cell

waste for example from the paper industry, or lingo-cellulosic biomass, secondary process flows from refineries and the chemical industry, bio-(m)ethanol and bio-diesel. However, the contaminant levels in these fuels are often unacceptable for durable performance of a molten carbonate fuel cell. This sets demanding requirements on the gas clean-up stage and it is thus desirable to establish precisely – and improve – the tolerance to residual contaminants of the fuel cell.
Schematically, the chain considered is shown in *Figure 1.*

Non conventional fuels

With alternative or non-conventional fuels we mean to indicate those fuels that are not fossil in origin (oil, coal, natural gas), but that are derivatives of energy resources which are the product of organic activity on the planet (waste and biomass) or of instantaneous energy flows (solar, wind, waves), and thereby renewable.
Here we want to consider the exploitation of the refuse flows of our society, in particular those of organic origin: biomass and Municipal Solid Waste (MSW).
Biomass and waste, by their very nature, are variable in composition, energy content and availability, which renders optimization and standardization of the processing plants difficult and operation of the latter something to monitor continuously.

Fuel conversion

The several ways to convert the raw energy-containing material into a suitable fuel for subsequent conversion to energy, are divided in "hot" and "cold" technologies, where the former adopt thermal dissembling of the organic compounds in the raw fuel to create a synthetic gas consisting essentially of hydrogen, carbon monoxide and dioxide, whereas the latter type of conversion is a process in which microorganisms break down biodegradable material in the absence of oxygen, with the production of biogas – a mixture of methane and carbon dioxide.
The product gas from the different fuel conversion technologies may vary considerably, even within the same method of conversion. Considerations such as fuel moisture, cellulosic structure, organic content and chemical composition, oxidant or bacterial utilization, thermal or pH management, reactor type and residence times all influence the quality of the final gas produced. Generally it is aimed to achieve contents as high as possible of light hydrocarbons, carbon monoxide and hydrogen for highest energy content.
Anaerobic digestion produces a superior quality gas rich in methane and has the benefit of yielding extra fertilizer, in the form of the digestate. Gasification is the most demanding of the technologies, but is very flexible in its feedstock.
Furthermore, using steam as a gasifying agent produces a high quality syngas rich in hydrogen and methane.

Anaerobic digestion

Anaerobic digestion is an established technology for environmental protection through bacterial treatment of organic substrates. Wastewater treatment facilities all over the world use anaerobic digestion to neutralise the organic compounds of sewage sludge.
Fermentation in the absence of oxygen is also being considered to treat animal manure. Currently, anaerobic digestion is receiving new attention as it can potentially reduce global warming thanks to (CO_2 neutral) utilization of the produced biogas as an energy source.
In anaerobic digestion, a process which takes place in the absence of oxygen, a mixed population of bacteria catalyses the breakdown of the polymers found in biomass to give biogas. This primarily consists of methane and carbon dioxide but may also contain ammonia, hydrogen sulphide and mercaptans, which are corrosive, poisonous and malodorous.
Although the composition of the biogas may vary considerably depending on the feedstock composition, the process conditions (bacteria species utilised, temperature, pH), and the type of digester used, a generally applicable composition can be given as:

CH_4: 55-65%, CO_2: 30-45%, N_2: 1-5%, H_2: 1-5%, H_2S: 80-4000 ppm.

Other pollutants (in particular ammonia, siloxanes, halogens) are present in traces (<1000 ppm).
The digestion process also generates a solid residue, which can be spread on site after composting treatment, and a liquor that can be used as a fertilizer.

Gasification

Gasification is the thermal decomposition of ground or pelletized solid fuel to a combustible gas, rich in carbon monoxide and hydrogen. By using a limited, sub-stoichiometric amount of oxygen in the thermal reaction, oxidation will be partial, thereby generating the heat required for the decomposition but maintaining abundant calorific value in the product gas.
In order to identify the best solutions for

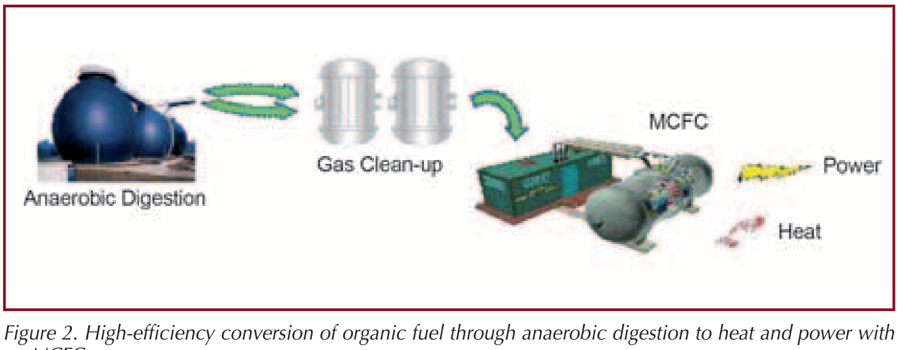

Figure 2. High-efficiency conversion of organic fuel through anaerobic digestion to heat and power with an MCFC

the coupling of a gasification process with a molten carbonate fuel cell the main aspects to optimize are:

- feedstock conditioning before conversion, in relation to the kinds of material put in
- gasifying medium
- produced fuel upgrading after the conversion.

Moisture content of freshly cut biomass is usually 30-60%. Fed biomass for fuel conversion is maintained at 10-20%, which means a drying step is usually necessary before feeding it into the reactor. The gasifier concept determines the exact moisture constraints, but also system optimization (varying syngas exit temperature and composition, minimum water content to prevent carbon deposition in the MCFC, bypassing fuel pre-drying for cost saving, etc.) has a considerable influence on what the ideal moisture content of the raw fuel should be.

A second important factor in gasifier operation is the fluidizing medium, which can be air, oxygen or steam. Air-blown gasifiers have the obvious advantage of using a medium which is available in abundance, but the large component of inert nitrogen can be cumbersome to the reactions. Using pure or diluted oxygen avoids this problem, but since a minimum amount of gas flow is required to fluidize the reactor bed, exaggerated oxidation or even combustion could occur, nullifying the gasifying process. Finally, using steam creates the extra difficulty of having to generate it, and the heat necessary for the gasification process is not supplied directly by the partial oxidation of the feedstock as it happens when air or oxygen is used. Therefore, an external heat supply is required, which can be provided by the combustion of recirculated syngas or of the char, residue of the gasification process, in a separate combustion chamber. Auxiliary fuel (e.g. anode off-gas) can be used if necessary. Steam gasification produces cleaner syngas with higher heating value, and richer in hydrogen than the other methods, without the diluting effects of nitrogen in air or the need of an expensive oxygen generation plant. For these reasons, it is probably the most suitable form of gasification for fuel cell applications.

At the end of the gasification stage some reduction of tars and char (respectively complex hydrocarbon compounds and carbonaceous residues, accounting for up to 10% of the syngas HHV but not utilisable in fuel cells) can occur, yielding extra production of H_2 and CO.

The temperature has to be sufficiently high for this endothermic reaction to take place (T≈1200°C).

Gas clean up

The MCFC can operate on a variety of different, non-conventional fuels, but the poisoning effect of some substances contained in these needs to be taken into account and resolved. Some species have a poisoning effect on the catalytic properties of the cell electrodes. The crucial link between the two technologies (non-conventional fuel production and MCFC), however, is formed by the gas clean-up step, since the produced gas contains trace elements that have detrimental effects on fuel cell performance and durability. To advance towards a speedy and successful coupling of biogas and fuel cells, it is necessary therefore, to contemporaneously:

- apply highly efficient gas cleaning, maintaining reliability and cost-effectiveness
- improve fuel cell tolerance to contaminants, facilitating system sturdiness and simplicity.

The tolerance levels of an MCFC stack regarding some relevant impurities mentioned in *Table 1* are indicative and the extent of their harmful effect may depend on the partial pressure of other species in the gas (e.g. hydrogen, carbon dioxide, water), the current density at which the fuel cell is operated and the fuel utilization factor.

The role of gas clean-up is to abate harmful contaminants like particulate, ammonia, hydrogen-sulphide, halogenated hydrocarbons and siloxanes from the fuel gas and thus to assure a higher degree of operational effectiveness and longevity of the downstream fuel-converting equipment, regardless of the technology utilised. For technical and operational reasons, the required degree of fuel gas purity differs largely between internal combustion engines (<1000 ppm), turbines (<70 000 ppm) and HTFCs like the MCFC (<1 ppm).

There are several methods to remove harmful impurities, which can be classified in two groups: physical-chemical (catalytic purification, adsorption, scrubbing, membrane separation, condensation) and biotechnological methods (biofilters, bioscrubbers, biotrickling filters).

Most of these biotechnological methods are cheaper than the physical-chemical ones having the same or even higher efficiency (99%) than these (though they cannot handle inorganic contaminants like siloxanes or particulates). Moreover, no chemicals need to be added, energy

Table 1. **Contaminants and their tolerance limits for MCFCs**

Contaminant	Tolerance	Effects	Cleaning method
Sulphides: H_2S, COS, CS_2	0.5-1 ppm	Electrode deactivation Reaction w electrolyte to form SO_2.	Methanol washing (T < -50°C) Carbon beds (T < 0°C) Scrubber (T < 100°C) ZnO/CuO adsorption (T < 300°C) High-T CeO ads. (T>700°C)
Halides: HCl, HF	0.1-1 ppm	Corrosion Reaction w electrolyte	Alumina or bicarbonate Activated carbon
Siloxanes: HDMS, D5	10-100 ppm	Silicate deposits	Ice absorption (T = -30°C) Graphite sieves
NH_3	1-3%	NB: Fuel at low conc. Reaction w electrolyte to form NO_x	Catalytic cracking Bag filter as NH_4Cl
Particulates	10-100 ppm	Deposition, plugging	Cyclone + bag/ceramic filter Electrostatic precipitator
Tars	2000 ppm	C deposition	Catalytic cracking T > 1000°C
Heavy metals: As, Pb, Zn, Cd, Hg	1-20 ppm	Deposition Reaction w electrolyte	Bag/ceramic filter Electrostatic precipitator

requirements are lower and there is no formation of secondary contaminant streams that need to be specifically treated. The main problem of these systems is their slow reaction under load fluctuations, which poses the risk of contaminant breakthrough.

Molten carbonate fuel cells: status

Fuel cells are characterised by extremely high theoretical efficiencies (in cogeneration over 90%), with a very high electrical component (up to 45-50% based on Lower Heating Value), and which remain high also in small-to-medium scale systems. Thus, for equal power production, the MCFC can significantly reduce the exploitation of non-renewable as well as renewable energy sources. In addition, a high efficiency is translated into reduced carbon dioxide emissions.

The MCFC operates at about 650°C, thus, differently from low temperature fuel cells, no precious metal is required as the fuel catalyst. Together with production cost saving, the main consequence of this is that carbon monoxide is not a poisoning element, but, on the contrary, it can be used as a fuel. This means that the operation of MCFC is not restricted to hydrogen availability, and allows the utilization of a variety of hydrocarbon fuels, such as natural gas, syngas derived from biomass or coal, landfill gas, gas derived from industrial or agricultural by-products. At present, for economical and ecological reasons, there is a strong interest towards the use of secondary fuels, by-products from various industrial processes.

The typical structure of an MCFC is schematically illustrated in *Figure 3*.

The electrolyte is embedded in a matrix as liquid phase. Ionic transfer inside the electrolyte is conducted via CO_3^{2-} ions migrating from the cathode to the anode side.

The chemical reactions that govern the operations are:

$$CO_2 + \frac{1}{2} O_2 + 2e^- \rightarrow CO_3^{2-}$$

on the cathode side, while, on the anode:

$$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$$
$$CO + H_2O \leftrightarrow H_2 + CO_2$$

of which the latter is commonly called water shift reaction and converts carbon monoxide and water into hydrogen. As a consequence of these reactions, water is formed in the anode side and CO_2 is needed on the cathode side. Since the CO_2 required for the cathode reaction is the same formed as consequence of the anode reaction, spent anodic gas is generally recycled back to the cathode.

Among the high-temperature fuel cell types, the MCFC benefits from advanced field experience and a more consolidated scientific background. Fuel cell systems based on MCFC technology are under development in Italy, Japan, Korea, USA and Germany. Since the 1990s, MCFC systems have been tested in field trials in the range between 40 kW_{el} and 1.8 MW_{el}. The growing number of MCFC installations in the world is mainly due to the strong role played by the American Company, Fuel Cell Energy (FCE) and the German MTU On-Site Energy in putting their products in operation. MTU developed its 250 kW system, called the Hot Module, based on FCE's fuel cell stacks.

Six developers are considered as the major in the world:

1. FuelCell Energy (FCE, USA)
2. GENCELL Corporation (USA)
3. MTU ON-Site Energy (MTU, Germany)
4. Ansaldo Fuel Cells (AFCo, Italy)
5. Ishikawajima-Harima Heavy Industries (IHI, Japan)
6. POSCO/KEPCO consortium (Korea).

A comprehensive review of these developers has been published in last year's edition of "Energies from Italy" and gives an overview of the current status of their production strategies and achievements. At this time, molten carbonate fuel cells have been demonstrated at several sites, and in different sizes. Focus is mostly on the 200 kW-1 MW range, while scale-up to multi-MW power plants are underway. High investment cost and reduced durability compared to conventional technologies are still two important issues to overcome, in order to ensure proper market penetration. Therefore, R&D activities are still needed before the technology can be considered mature enough to compete with traditional energy systems.

Nevertheless, there are interesting applications where MCFCs already make economical sense. These include applications where gas is available as a by-product of an industrial of agricultural process, where stringent environmental requirements are in place, and/or where Combined Heat and Power (CHP) off-take is guaranteed. Importantly, due to the high quantity of methane in many alternative, renewable fuels, the established grid of natural gas could function as a widely available stepping stone for the large-scale implementation and acceptance of high-temperature fuel cells, and facilitate their insertion in non-conventional applications.

MCFC fed with non conventional fuels

Seeing that non-conventional fuels are characterized by lower energy contents than their fossil equivalents, their exploitation must be the most efficient possible to be able to keep the conversion process slim and manageable. Fuel cells have the potential to achieve over 50% electrical efficiency and are thereby still the most efficient conversion technology, as they are not affected by heat engine (Carnot) limitations. Moreover, emission levels are considerably lower than conventional, combustion-based technologies.

Alternative energy sources are generally characterised by a large fraction of fixed

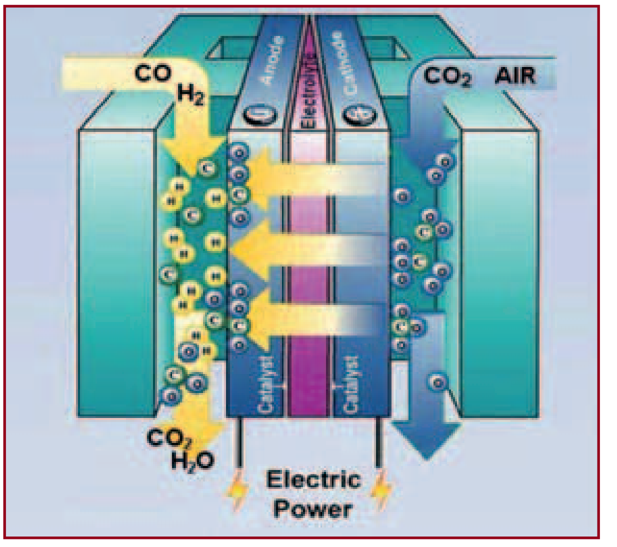

Figure 3. Schematic representation of a functioning MCFC

carbon and a conspicuous amount of contaminants, so that MCFCs are the most appropriate, being more tolerant to these compounds than fuel cells operating at low temperature.
In addition to cost reduction, this implies that carbon monoxide does not exhibit any poisoning effect on the fuel cell, and on the contrary can be used as an additional fuel. Since the fuel cell system is by principle of a modular build-up, it is eminently suitable for decentralised, small-to-medium scale CHP applications (0.1-10 MW), since at larger sizes (>100 MW) conventional combined cycle plants approach the high efficiencies that are the characteristic of a single fuel cell. Hence, MCFCs will find their ideal allocation in decentralised, grid-independent residential and small industrial heat and power supply, as well as providing premium power to utilities that rely on constant availability. The current MCFCs' rather demanding level of purity of the fuel gas and the risks of contaminants – in particular sulphur compounds, as H_2S – breaking through a cost-effective clean-up system, mainly due to the fluctuating composition of the non conventional fuel, as biogas from anaerobic digestion, strongly encourage the development of more resistant materials for cell operation.
H_2S has an immediate effect on cell performance, even at 2 ppm. The effects of low concentrations of H_2S in the fuel are due to interaction with the electrolyte and with the anode surface. The poisoning effect persists for a cell operated at dry conditions: reversal of the effect can be accentuated by increasing water content in the fuel flow.
At system level, this implies that a breakthrough of sulphurous contaminants from the gas clean-up stage can be detected immediately in cell performance. For H_2S concentration peaks of up to 100 ppm lasting up to 24 hours complete recovery of the MCFC can be achieved, especially introducing higher degrees of water content at the anode.
The main aim of several international projects is finalized towards the coupling of a MCFC to an anaerobic digestion process or gasification process of different biomass/residues. For example, in the case of biogas, the gross composition of the gas produced is ideally suited for electrochemical conversion in an MCFC due to the large quantity of readily reformable methane and the necessary diluent CO_2 and several demonstration projects have already been launched that prove the strong potential of anaerobic digestion coupled with MCFC heat and power generation.

Table 2. **FCE installations fed with biogas**

Project Name	Application	Date in Service	Nominal Power
King County, CA (USA)	Waste Water Biogas	06/2004	1 MW
Kirin (Japan)	Digester Gas from Brewery Process	09/2003	250 kW
Fukuoka (Japan)	Waste Water Biogas	01/2004	250 kW
Palmdale, CA (USA)	Waste Water Biogas	08/2003	250 kW
Santa Barbara, CA (USA)	Waste Water Biogas	09/2003	500 kW
Tancheon, Seul (Korea)	Sewage Digester Gas	04/2006	250 kW
Super Eco Town, Tokyo (Japan)	Anaerobic Digester Gas from Food Recycling Facility	06/2006	250 kW
Sierra Nevada , CA (USA)	Biogas (waste by-product of the brewing process)	05/2005	1 MW
Terminal Island, San Pedro, CA (USA)	Sewage Digester Gas		250 kW
KEEP (Japan)	Waste Water Biogas	01/2006	250 kW
Tulare, CA (USA)	Waste Water Biogas	10/2007	900 kW
Dublin-San Ramon, CA (USA)	Waste Water Biogas	03/2008	600 kW
Chevron Energy Solutions, Rialto CA (USA)	Operated on biogas from waste water and kitchen grease	10/2007	900 kW
Southern California Gas Company, Riverside CA (USA)	Operated on biogas from waste water treatment	08/2008	1 MW
Turlock, CA (USA)	Waste Water Biogas	10/2008	1.2 MW
Moreno Valley, CA (USA)	Waste Water Biogas	10/2008	750 kW
Gills Onions, CA (USA)	Biogas from onion peel waste	10/2008	600 kW
Livermore, CA (USA)	Waste Water Biogas	Construction	600 kW
Point Loma, CA (USA)	Waste Water Biogas	Construction	300 kW
San Diego	Waste Water Biogas	Construction	1.2 MW
UC San Diego	Waste Water Biogas	Construction	2.4 MW

DEMONSTRATION SYSTEMS IN THE WORLD

Several developers have usefully demonstrated the MCFC's performance and flex-

Figure 4. King Country Wastewater Treatment Facility Renton - Washington, USA

ibility in decentralized and niche applications, and an increasing number of small-to-medium-scale plants (250 kW-2 MW) are being installed over the world, particularly where stringent environmental constraints are in place (e.g. California) or strong government backing and vision provide impetus to their implementation (e.g. South Korea). In the following tables an overview is given of the demonstration projects operating on different fuels, principally on biogas, by developers FuelCell Energy (FCE), MTU On-Site Energy (MTU) and Ansaldo Fuel Cells.

FCE - USA

Significant world-wide operational experience has been accumulated with 250 kW power plants running on different fuels and for various applications.

Their systems were originally developed for being operated on natural gas, but other fuels like biogas, landfill gas, coal gas, mine gas, residual gas, were considered as optional feedstock.

The following table shows those fuelled by alternative fuels, biogas in particular, which constitute more than 20% of the total installations.

MTU - Germany

MTU On-Site Energy developped their CHP systems using the stack technology of FCE.

Among their field experience several plants have achieved over 30000 hours of service life, and many new applications are being installed. The following table shows those fuelled by alternative fuels, biogas in particular.

Table 3. **MTU installations fed with biogas**

Location	Application	Nominal Power
Ahlen (Germany)	Waste Water Biogas	250 kW
Leonberg (Germany)	Anaerobic Digester Gas from "green bin" waste treatment	250 kW

ANSALDO Fuel Cells (AFCo) - Italy

The following table shows those fuelled by alternative fuels, biogas in particular.

Presently, the only MCFC demonstration project that will be operated on syngas from a gasification process is the AFCo 125 kW stack which is being coupled to the 500 kWth gasifier Joule on the ENEA premises of the Trisaia research centre *(see figure 4)*. The dual fluidized bed steam gasification pilot plant, shown in *Figure 4*, is able to produce a hydrogen-rich and nearly nitrogen-free gas.

According to the experimental results, using wood chips or almond shells as feedstock, the hydrogen percentage reaches 40% vol. on dry basis and the higher calorific value approaches 13 MJ/Nm^3.

The system is provided with both a conventional cleaning section and an advanced hot gas cleaning section. The latter allows to reduce the concentration of particle and acid compounds in the produced gas to very low levels.

The main objectives of the research activity integrating the MCFC with the operational gasifier will be:

- to demonstrate the technical feasibility of using directly the produced gas from a gasification plant as anodic feed for the MCFC;
- to assess the related MCFC performances;
- to test the MCFC with different fuel gases simulating the gas produced by different biomass conversion processes (air gasification, anaerobic digestion, etc.);
- to explore the potential of commercial applications of integrated biomass gasification fuel cell systems.

The demonstration program represents a key part of the present phase of development of AFCo.

The final goal of the program is to demonstrate the technology viability for different fuels and applications, with a total installed power of over 4 MW.

Table 4. **Demonstration program at Ansaldo Fuel Cells fed with biogas**

Size (Class)	Fuel	Site	Objectives	Support
125 kW	Biomass gasification	ENEA Trisaia, Italy	Demonstration biomass gasification/fuel cell integrated process	EC/Italian Ministry of University & Research
MW class	Waste water ADG, Landfill	Terni, Italy	Scaling-up with ADG and landfill	EC

Figure 5. Anaerobic digester gasfrom green bin waste treatment - Leonberg, Germany

Figure 6a. Gasification plant (ENEA Trisaia research centre)

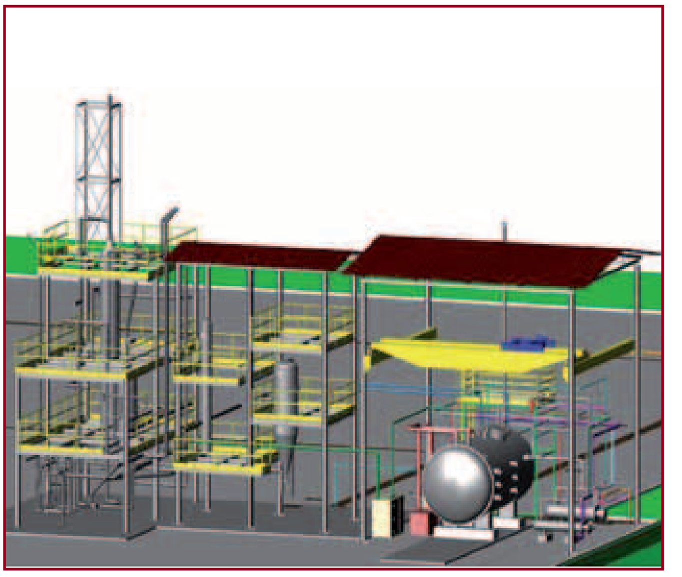

Figure 6b. Integrated plant: gasification and MCFC (ENEA Trisaia research centre)

CONCLUSIONS

An overview has been given of the chain from alternative, non-conventional fuels (in particular waste and biomass) to electricity and heat produced by a Molten Carbonate Fuel Cell. In the light of our dependence on primary energy carrier imports and the current environmental and political necessities, using biomass and waste to produce alternative fuels is a high quality solution, especially when integrated with high efficiency fuel cell applications.

Since these non-conventional fuel sources are generally poor in energy content, their successful exploitation resides in their decentralised application; an attribute which characterises fuel cell systems adamantly. For distributed CHP generation, furthermore, it has been shown that high-temperature fuel cells, like MCFCs, are the most promising due to their suitability for carbon conversion, inherent sturdiness and increasing reliability, and the quality of heat and power produced.

The concentration, composition and harmfulness of the fuel gas to be utilised varies with the upstream technology of conversion: anaerobic digestion and gasification were considered, and the dependency of the gas composition on operational parameters was briefly touched upon.

Controlled digestion of organic material yields superior quality gas and an extra useful product in the form of the digestate and liquor, which can be utilised excellently as fertilizers and soil regenerators. Gasification is more versatile in its feedstock, but the most demanding in terms of technology. Steam gasification is the best way of producing a syngas suitable for high-temperature fuel cell systems.

However, before large-scale deployment of waste or biomass-based systems can be realised, the issue of contaminants in these fuels needs to be adequately resolved. An overview of current tolerance levels to the most frequent contaminants was given as they are known today. Especially sulphur compounds are harmful to fuel cells, but also siloxanes, halides and fluorides are damaging, and their extraction from the fuel gas is not always easy down to the required concentrations. Add to this the strong dependence on operating conditions and different reversing potentials of each poisoning effect, and it is clear that there is still considerable room for improvement in the accurate tuning of required fuel properties by the MCFC and cost-effective fuel cleaning. ■

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