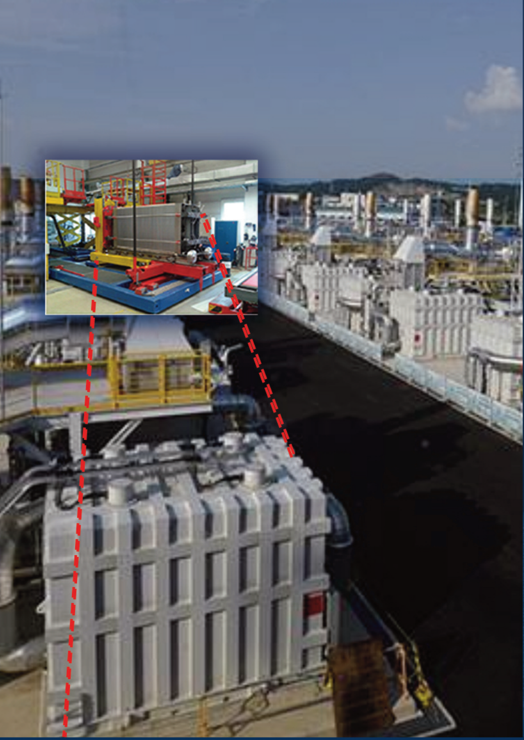

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Italian National Agency for New Technologies,
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DOSSIER

INTERNATIONAL STATUS OF MOLTEN CARBONATE FUEL CELLS TECHNOLOGY

2015

Stephen J. McPhail, Luigi Leto, Massimiliano Della Pietra,
Viviana Cigolotti, Angelo Moreno

iea Energy Technology Network

Advanced Fuel Cells Implementing Agreement
Annex 23 - MCFC

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PREFACE

Reducing our carbon footprint is widely acknowledged as one of modern society's top priorities, as well as building a sustainable economy based on knowledge and innovation for enduring opportunities of development. Molten carbonate fuel cells (MCFC) offer rich potential in these terms as a forward-looking and highly flexible way to reduce CO_2 emissions providing more efficient and cleaner, greener energy, making use of both fossil and renewable sources.

MCFCs are a key technology for stationary applications, especially in the size of hundreds to thousands of kilowatts, which is a very interesting power range in view of the increasing decentralization of energy supply and the increased need for high-quality power independent of the grid. After several years of research programs and extensive demonstration, MCFC-based systems are now appearing in commercial ventures of multiple megawatts, providing clean energy to commercial and small/mid-size industrial customers all over the world. Especially in this phase of early deployment, and with a view to stay at the forefront of smart solutions for the evolving energy paradigm, to improve the technology, increase reliability and reduce manufacturing costs, a lot of effort is still required from research and development to safeguard the relevancy and make real the enormous potential of MCFC solutions in the near and long-term future.

The present report attempts to provide an accurate review of the current status of MCFC technology and deployment in the world. The basic principles will be introduced briefly and an overview of currently operational power plants will be set against a perspective of innovative system applications with great future market potential. The main stakeholders in this highly fertile field will be pointed out together with their core competences and contributions to the advancement of the technology.

Contents

1. Molten Carbonate Fuel Cells: the Basic Principles

Fuel Cells are highly efficient electrochemical reactors which convert the chemical potential of a fuel directly and noiselessly (without moving parts) into electrical energy. This happens without combustion, strongly reducing environmental impact while producing electricity and heat at very high efficiencies. The Molten Carbonate Fuel Cell (MCFC), in particular, works at high temperature (about 650 °C) and this brings with it several advantages.

This high operating temperature allows for increased performance as well as the opportunity to cogenerate high-quality heat and/or cooling with the electric power, for various purposes. MCFCs do not require particularly expensive materials to function, as opposed to low-temperature fuel cells which require Platinum as a catalyst. They may be fuelled with any gaseous form of hydrogen (and carbon), generating steam (and carbon dioxide) as end-products.

1.1 How the molten carbonate fuel cell works

A working MCFC system is made up of individual cells which are stacked to make up any desired power. The individual cell, in turn (see Figure 1), consists of an anode and cathode where the conversion processes take place, joined by an electrolyte which closes the electrical circuit.
Both anode and cathode are nickel-based whereas the electrolyte consisting of harmless salts of lithium, potassium and sodium carbonates in molten state and suspended in a porous ceramic matrix.
The nickel anode is also an excellent catalyst for reaction the so-called “shift reaction” which converts carbon species (ultimately carbon monoxide) and water into hydrogen, which then releases the electrons which generate the electric current. As a consequence, the MCFC can operate with both pure hydrogen as well as hydrocarbons, and water is formed at the anode side.

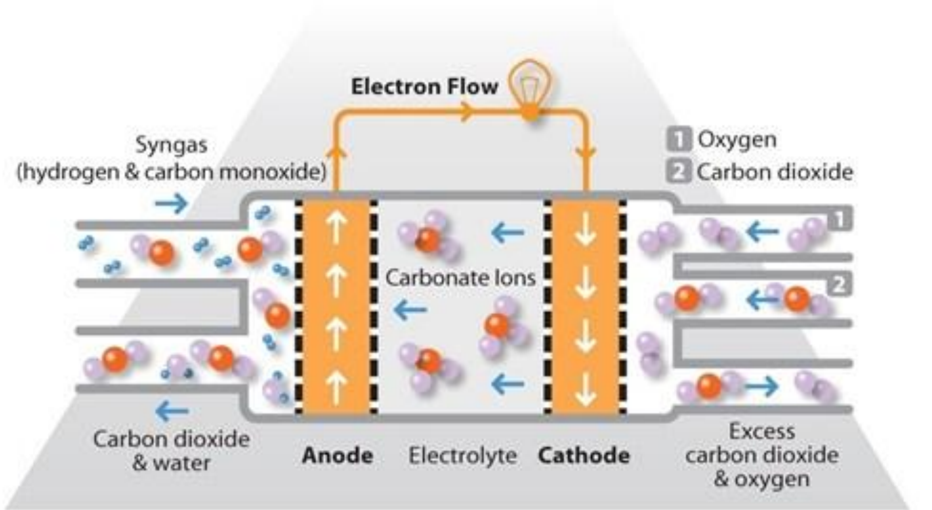

Figure 1 – Schematic representation of the operation of an MCFC [source: www.fuelcelltoday.com]

What is particular to MCFCs is that carbon dioxide is necessary as a closed-loop reagent: at the CO_2 is consumed at the cathode (together with oxygen) at the same rate at which it is released at the anode. This role of CO_2 will be taken up later as it provides an interesting opportunity to use the MCFC to separate CO_2 from the flue gas of combustion-based power plants.

1.2 High efficiency

MCFCs are particularly suited as steady state cogenerators, in small-to-medium commercial and industrial applications requiring from hundreds to thousands of kilowatts of power, in decentralized and isolated plants, but also for customers who require reliable, high-quality power independently from the grid. Making use of the high-temperature process heat that is produced, an overall efficiency on the inlet primary energy can amount to 90%, of which up to 48-49% is electric power – the highest achievable value for this scale of plants as is illustrated in Figure 2.

The MCFC's ultimate performance is influenced by many operating conditions which depend on the ultimate application, such as load profile, availability, power-to-heat ratio required, fuel and oxidant chemical compositions. But the MCFC's excellent capacity to work also at part load – with practically unchanging efficiency values – makes it a technology which comes out head and shoulders above conventional generators in the intermediate power range.

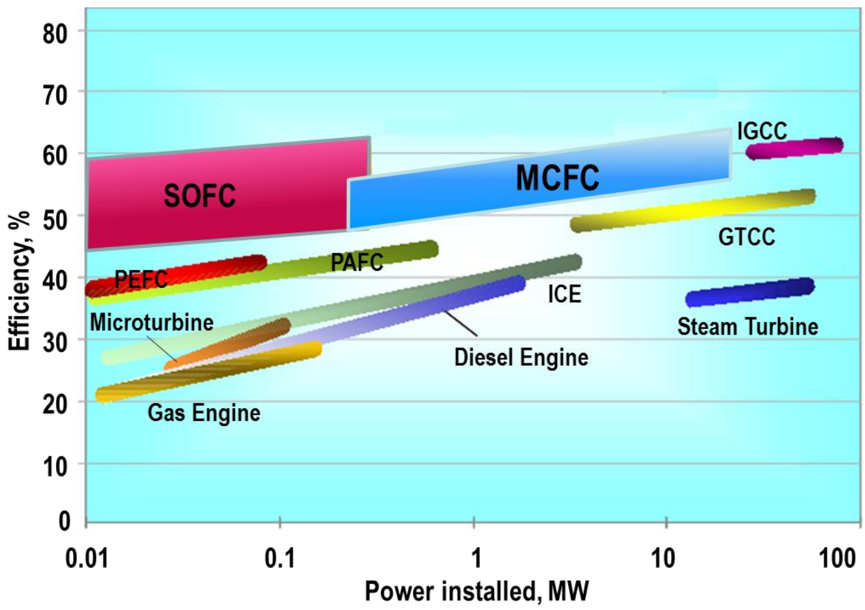

Figure 2 – Comparison of electric efficiency vs. power installed for combustion-based systems and fuel cell systems (ICE = Internal Combustion Engine, GTCC = Gas-Steam Turbine Combined Cycle, ICGG = Integrated Gasification Combined Cycle, PEFC = Polymer Electrolyte Fuel Cell, PAFC = Phosphoric Acid Fuel Cell, MCFC = Molten Carbonate Fuel Cell, SOFC = Solid Oxide Fuel Cell [source: ENEA, www.enea.it]

1.3 Fuel flexibility

As mentioned, the MCFC can be fed with any hydrogen-carbon mixture as fuel, therefore a variety of fuels such as natural gas, biogas, gasified biomass, syngas from coal or waste, but even liquid fuels such as ethanol can be adopted. The high operating temperature of the MCFC helps to process all these different fuels, but for safe and enduring operation of the MCFC a careful *clean-up* of the fuel is necessary beforehand, as they are less tolerant to impurities than combustion-based systems. This has the inherent benefit that whatever is expelled from the MCFC is automatically clean as well, which is why they are called ultra-clean power generators.

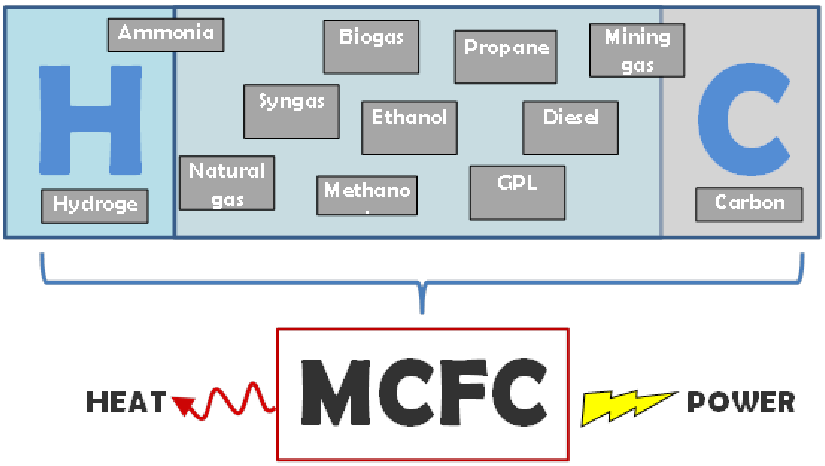

Figure 3 – The fuel flexibility of MCFCs
[source: ENEA, www.enea.it]

1.4 Low emissions

The MCFC, unlike traditional reciprocating engines and gas turbines, produce virtually no nitrous oxides (NOx), volatile organic compounds (VOCs) or particulates, because the operating temperature is lower than that of combustion Furthermore, by combining fuel and air electrochemically, a clean and direct transformation of the chemical energy to electricity is achieved, a benefit intrinsic to fuel cells. The electrochemical process requires fuel compositions to be as clean as possible, which implies that all outlet gases are clean as well, as mentioned above. For example, sulphurous compounds are not emitted because they are highly poisonous for the fuel cells and they need to be extracted before the electrochemical process.

1.5 Target applications

The MCFC may be effectively carbon neutral and emit zero net greenhouse gases when it is fed with renewable fuels, such as biogas. The carbon dioxide produced on the anode side which is not recirculated to the cathode is simply the result of the carbon-based species that are fed at the

inlet. But even if fossil natural gas is used as a fuel, because of the higher efficiency of the MCFC, less CO_2 is emitted because less primary fuel is required to produce a given amount of electricity.
MCFC plants are suited for a wide variety of markets and applications, spanning industrial, institutional and utility customers. Distributed power generation with MCFC technologies can significantly reduce reliance on the already strained power grid. Other technologies relying on certain operating conditions, such as solar and wind, generally achieve availability ratings of 25% to 35%. MCFC power plants achieve availability ratings of about 95%, offering base load power 24 hours a day. What follows are a few examples of niche applications where MCFC systems are already being used to save primary energy, provide independence from the grid and reduce emissions.

Food and drink processing

MCFC power plants are suited to food and drink processing applications which generate anaerobic digester gas. An additional benefit for the food and beverage industry is the Combined Heat and Power (CHP) capabilities inherent to the stationary MCFC plants. Harvesting waste heat, steam can be produced for hot water and other heating needs, further increasing the efficiency of the power plant, up to double that of grid-supplied power. Because most food and drink processing plants require 5 MW or less of power, fuel cell power plants can produce most, if not all, of the power requirements at these facilities. In places where digester gas production volume is variable, blending with natural gas can be carried out for reliable base-load power and heat.

Hospitals, Prisons

Facilities with critical power requirements, such as hospitals and prisons, depend on a constant source of power, and interruptions to that power supply can lead to dangerous consequences. Existing sources of back-up power at these facilities such as generators and battery packs, are intended for short-term emergency use, and could not be used in the event of a long-term interruption to the power grid. In addition to having a reliable, prime power source on-site, the efficiency of MCFC power plants contributes to measurable energy savings.

Hotels and manufacturing

Also where interruptions to the grid can lead to significant loss of revenue, MCFC plants can provide a reliable solution. Hotels and manufacturing plants could benefit from on-site fuel cell power plants as a reliable source of baseload power, generating not only electricity for the facility and heat for hot water, process or space heating, but also considerable publicity towards customers who appreciate the “green” aspect of the plant.

Colleges and Universities

The importance of improved CHP solutions is magnified for institutions of higher learning, where students, faculty, alumni and trustees expect campuses to be a leading example balancing environmental impact and energy expenses. In addition, growing enrollments, larger campuses, and critical power requirements of research laboratories are driving the demand away from the power grid. An additional benefit unique to higher education facilities is that an MCFC plant offers real-world research opportunities for faculty and students.

Utilities

With power requirements in the industrialized countries estimated to be three times the level of the year 2000 by 2020, utility companies are facing increasing difficulties accommodating escalating power loads. The aging of energy transmission networks, grid congestion, and the development of increasingly remote areas and developing countries are concerns that have utilities seeking alternatives to traditional forms of supplying power. The answer lies with distributed generation. Rather than build a costly transmission system to provide power to remote or congested areas, utility companies can use distributed generation to supply customers in those areas with a constant supply of power. Stationary fuel cell power plants are an ideal solution for such applications.

1.6 Investment and running costs

At the time of writing, fuel cells systems are on average still 3-4 times more expensive in terms of capital investment than conventional distributed generation, see Table 1.

	Diesel Engine	Gas Engine	Gas Turbine	Steam Turbine	Fuel Cells
Investment Cost ($/kW)	1,100 ~ 1,300	1,100 ~ 1,300	2,000 ~ 2,500	1,100 ~ 1,300	4,000 ~ 6,000

Table 1 – Investment costs for various types of power generating technologies
[source: POSCO Energy, www.asiacleanenergyforum.org, 2013]

Reduction of system manufacturing costs is certainly expected with increasing mass production. However, capital cost is only part of the story. The capital cost of a diesel generator is very low but the operating cost is very high due to the poor electrical efficiency and high fuel use. It also has a poor emission profile and is noisy and thus is not in the same market or application segment as what MCFC systems target. As stated in section 1.5, a hospital or university will hesitate to use diesel generators for prime power nor would a utility use 15-100 MW of diesel generators for baseload grid support.

A great advantage of a system like the MCFC is that in comparison with other technologies, it is less dependent on fuel costs due to their higher generation efficiency. This is expected to become an increasingly pressing factor for the future, where these costs will tend to become more volatile (see Table 2).

		'07	'13	
Investment Cost	U$/kW	9,000	4,500	△50%
LNG Cost	U$/Nm³	0.35	0.80	129%
Generation Cost	U$/kWh	0.20	0.26	30%

Table 2 – Breakdown of power generation costs for MCFC
[source: POSCO Energy, www.asiacleanenergyforum.org, 2013]

A useful quantity to consider in this respect is the levelized cost of energy (LCOE). The LCOE is calculated by accounting for all of a system's expected lifetime costs (including construction, financing, fuel, maintenance, taxes, insurance and incentives), which are then divided by the system's lifetime expected power output (kWh). All cost and benefit estimates are adjusted for inflation and discounted to account for the time-value of money, so that the LCOE is very valuable, as a financial tool, for the comparison of various power generation options. Furthermore, the high availability of an MCFC system (over 90%) compared to other power generation technologies, makes the calculated LCOE extremely reliable.

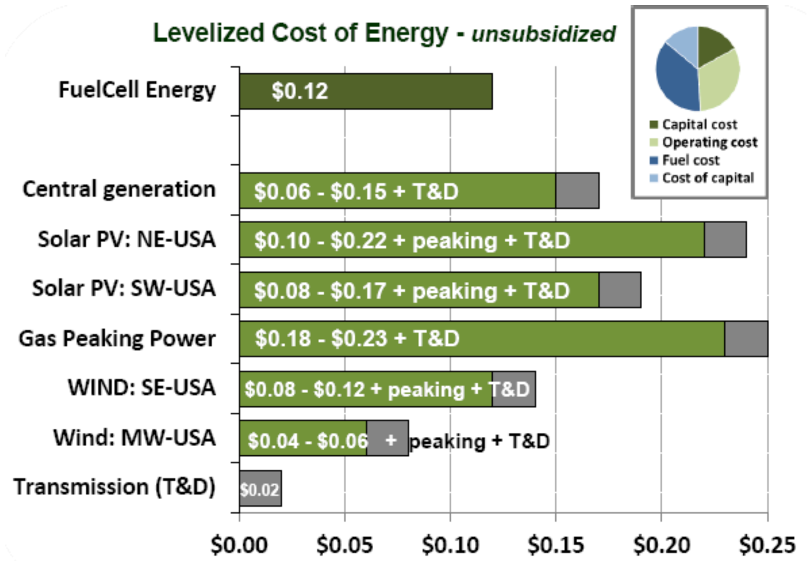

Figure 4 – LCOE for various power generation technologies compared with the MCFC
Based on US$4.50/MMBTU (around US$0.17/Nm^3) of natural gas cost
[source: Lazard LCOE v 8.0, www.lazard.com; FuelCell Energy, www.fuelcellenergy.com]

As can be seen from figure 4 above, the LCOE for MCFC systems is already competitive compared with central generation and solar PV in the USA. In their analysis, investment bank Lazard estimates the LCOE of a diesel generator at about US$0.30, and – crucially – does not place a cost on emissions, waste disposal, transmission and distribution or land acquisition costs, all of which can be material factors in urban environments and attributes of MCFC power generation solutions. And of course, what value does society place on the lack of harmful emissions?

2. Introducing the MCFC Players in the World

2.1 MCFC Technology Producers

FuelCell Energy, FCE (USA)

Company

Based in Danbury, CT (USA), FuelCell Energy (Nasdaq: FCEL), with more than 40 years of experience, are a global leader in the manufacture and commercialization of stationary electric power generation. FuelCell Energy operates a manufacturing plant in Torrington (CT), with a capacity of 90 MW per year. The company's Direct FuelCell® (DFC®) power plants have generated ~3.0 Billion kW hours of electricity and are generating power at more than 50 installations worldwide. FuelCell Energy's headquarters act as the nerve center for the company's commercial, industrial, and grid-support applications deployed worldwide. Danbury is also the hub for the company's Global Technical Assistance Center which is staffed 24 hours per day, seven days per week and 365 days per year to remotely monitor and operate DFC power plants worldwide.

In 1992 their first, 120 kilowatt (kW) high temperature carbonate fuel cell system was successfully demonstrated, and in 1996 a 2 megawatt (MW) DFC power plant went online in Santa Clara, California. Ten years later, the company possessed a product line offering systems from 300 kilowatts (kW) to 2.8 megawatts (MW), scalable up to over 100 MW.

Core products

The complete line of carbonate DFC® products by FuelCell Energy, the sub-megawatt 300 kW DFC300®, the 1.4 megawatt DFC1500® and the 2.8 megawatt DFC3000® power plants, has been designated as "Ultra-Clean" under 2007 California Air Resources Board (CARB) standards.

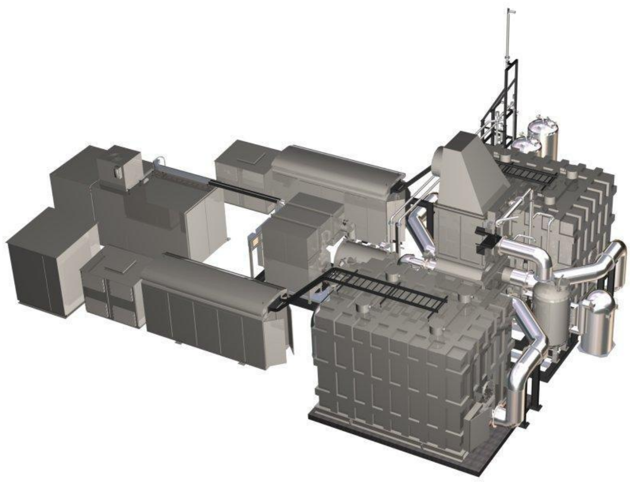

Figure 5 – FuelCell Energy's DFC3000 MCFC power plant comprises three major functional elements: Electrical Balance of Plant, Mechanical Balance of Plant, and Fuel Cell Modules [source: FuelCell Energy, www.fuelcellenergy.com]

Developed exclusively for use in stationary applications, FuelCell Energy's systems are self-contained electrical power generators capable of providing high-quality base load power with 47% electrical efficiency, 24 hours a day, 7 days a week. Featuring ultra-low emissions, low operating noise, and a small footprint, they are suitable for locations where traditional power generation technologies are not feasible or desirable. The DFC products can be used for on-site power generation, cogeneration and Combined Heat and Power (CHP), and distributed energy grid support. Thanks to their modular design, DFC products can be assembled to make up any power class desired, even multi-MW power plants.

The DFC300 (6x4.5x6 m^3, 19 metric tons) generates 300 kW of power at 480 V and 50-60 Hz. Exhaust temperature is about 370 °C with 1800 kg/h of exhaust flow. This offers a cogeneration capacity between 140 and 235 kW.

The DFC1500 (16x12x6 m^3), consisting of water treatment skid, main process skid, electric balance of plant, fuel cell module, desulfurization, cogenerates between 650 kW and 1100 kW with 8300 kg/h of 370 °C exhaust flow.

FuelCell Energy's DFC3000 system is the largest of the DFC power plant fleet, consisting of two 4-stack modular skids.

Figure 6 – FuelCell Energy's core products in the field
[source: FuelCell Energy, www.fuelcellenergy.com]

Recovering energy from natural gas pressure let-down stations

Natural gas transmission networks utilize long-distance pipelines operating at very high pressures. These pressures are required to maintain a high volume of flow in the system. Gas distribution to homes and businesses, however, uses a much lower pressure for safety and to accommodate end use equipment. Pressure is reduced at local utility letdown stations to accommodate the distribution network. As pressure is reduced, the gas naturally cools because of the refrigerant effect of gas expansion. To prevent the gas systems and pipeline from freezing, the gas must be heated before it flows through the expansion process. Traditionally, the energy available in this letdown process is lost, and gas-fired boilers, which produce local emissions and CO_2, provide the heat needed by the process.

The hybrid, multi-megawatt DFC-ERG™ (Direct FuelCell Energy Recovery Generation™) system has been developed to recover this significant amount of high-quality energy more efficiently, combining a Direct FuelCell® power plant with an unfired gas expansion turbine. The DFC-ERG is unique, with electrical efficiencies exceeding 60%, low noise, and virtually zero smog emissions.

The energy normally lost when natural gas expands is harnessed by the turbo expander to drive an electric generator. The DFC, operating on pipeline gas, produces additional electric power. Waste heat from the DFC provides the heat required by the expansion process, replacing fuel used in gas-fired boilers. The utility grade electric power produced by the turbo expander and DFC system can be used for on-site power requirements and the power grid. Enbridge, Inc. (NYSE: ENB) is the exclusive distributor of the DFC-ERG power plant for North America.

Renewable power and heat from biogas

More than half of FuelCell Energy's installations and backlog in the state of California operate on renewable biogas. Building on early project lessons and design improvements FCE has executed several DFC300 and DFC1500 projects. Except for one older unit, all current biogas DFC plants have incorporated the natural gas backup with blending option to ensure fuel supply reliability. FCE products are increasingly being used at waste water treatment facilities in California. The projects are now tending to involve higher capacities: multiple subMW units or MW-scale units for more favorable plant economics.

Market perspectives

State and federal incentive programs for purchasing and operating clean technologies such as DFC power plants make these products an attractive alternative to traditional power generation systems. Programmes are in place providing capital cost rebates as well as feed in tariffs which will provide support for power sales directly to utilities.

States seeking to secure cleaner energy sources are legislating Renewable Portfolio Standards (RPS) to mandate that utilities provide a certain amount of their electricity from renewable sources such as solar, wind and biomass: fuel cells are often claimed as equivalent to these sources due to their primary energy saving potential. In the USA there are currently 27 states and the District of Columbia that have instituted RPS mandates and 5 states that have adopted non-binding renewable energy goals. These markets represent a potential for an estimated 77 GW of renewable power by 2025, according to the Union for Concerned Scientists. Fuel cells using biogas qualify as renewable power generation technology in all RPS states, with nine states specifying that fuel cells operating on natural gas are also eligible for these initiatives.

The South Korean Government passed a RPS in March 2010 that requires 4 % clean energy generation by 2015 and 10 % by 2022. At present, only about 1 % of South Korea’s electricity comes from renewable resources. Fuel cells are an excellent green energy solution for South Korea due to the high cost of imported fuel and the poor wind and solar profiles of the Korean Peninsula. The South Korean government desires clean distributed generation power sources to support their growing power needs while minimizing additional investment and congestion of the transmission grid. Fuel cells address these needs and are designated as an economic driver due to their ultra-clean emissions, high efficiency and reliable distributed generation capabilities, which will help South Korea achieve its RPS and electricity generation goals. FCE currently have more than 50 sites operating with customers in 9 countries, totalling more than 300 MW of power generating capacity installed and in backlog.

2.2 MCFC Technology Integrators

POSCO Energy (South Korea)

POSCO Energy, a subsidiary company of POSCO, is the largest private power-generating company in Korea with a facility capacity of 1,800 MW. It has played the role of leader in the business, with large numbers of professionals and accumulated know-how from over 40 years of experience in building and operating power plants. POSCO Energy is planning the move to become the world's number one energy company, aiming to commercialize next-generation fuel cells and achieve a 10% world market share.

POSCO Energy has promoted technology development of MCFC since early 2000 as a government supported project. In this government project, POSCO Energy in collaboration with KEPCO has developed an external reforming-type MCFC and they have successfully operated a prototype 125 kW system in 2010. Also, since 2007, POSCO Energy has a strategic license, manufacturing and distribution agreement with USA's FuelCell Energy (see section 2.1) to market the latter's DFC units and manufacture both stack and balance-of-plant (BOP), capitalizing on POSCO's strong manufacturing capabilities and economies of scale to improve the system cost.

POSCO Energy brought about the development of the BOP in Korea by building a fuel cell manufacturing plant in Pohang with a yearly production capacity of 100 MW as well as an integrated service center and R&D center. As from 2010, the plant for the production of stacks that comprise the core technology is under operation with a capacity of 100 MW. Facilities for cell production with a capacity of 70 MW are under construction aiming to achieve full operation by July 2015.

Until now, POSCO Power has provided Gyeonggi, Geonra, Gyeongsang and Chungchung provinces with MCFC plants of 8.8 MW and in 2011 14 MW was provided to Suncheon, Dangjin, Ilsan and Incheon. Accelerating production and deployment, the 11.2 MW plant in Daegu City followed in 2012, and the world's biggest operating fuel cell plant was inaugurated in 2013: 59 MW (see Figure 7) providing prime power and district heating to the city of Hwaseong. As of November 2014, a total of 144.6 MW is being generated by MCFC plants at 18 sites in Korea.

POSCO Energy is paving the way to reach international markets such as Japan and Southeast Asia based on the experience and technology gained in the domestic market, and already a 120 MW contract has been agreed with FuelCell Energy to fulfil the necessary cell supply.

Figure 7 – The world's largest operating fuel cell power plant (59 MW), located in Hwaseong, South Korea [source: E4Tech, www.FuelCellIndustryReview.com]

FuelCell Energy Solutions, FCES (Germany)

Company

Fuel Cell Energy Solutions GmbH is a Joint-venture of FuelCell Energy, Inc. and Fraunhofer IKTS which continues the research to further enhance MCFC technology, combining the strength of FCE`s Direct FuelCell-technology and the 'EuroCell'-Technology, which will be licensed to the company by Fraunhofer IKTS.

FuelCell Energy Solutions (FCES) exists since May 2012 but the know-how and the experience reaches further back. As a subsidiary of FuelCell Energy and Fraunhofer IKTS, FCES combines the technological strengths of Fraunhofer with the commercial strengths and worldwide experience of FuelCell Energy from the USA with more than 80 installations. Fraunhofer inserts patents, assets and IP retrieved from MTU Onsite, a former fuel cell manufacturing company, as well as about 150 experts for fuel-cell-technology and ceramic materials, powder and pastes. With these two parent companies FCES guarantees full coverage of industrial fuel cell technology for customers. The special portfolio of FCES includes R&D, production and engineering as well as installation and commissions and long term full-service.

Based in Dresden, Germany, FCES is the partner of FuelCell Energy for the European Served Area. With manufacturing facilities in Ottobrunn, FCES builds stationary MCFC power plants that generate electricity with up to almost twice the electrical efficiency of conventional fossil fuel plants. With the help of these power plants FCES is offering efficient, reliable and economic energy where it is needed – without emissions damaging the environment. FCES offers the whole cycle for fuel cell power plants starting with R&D, manufacturing, sales, installation and service for the systems. Keeping the manufacturing of high technology fuel cell power plants in Germany, FCES creates sustainable jobs for Europe.

Core products

In addition to the core products marketed for FCE in Europe (respectively the DFC300 EU, DFC1500 EU and the DFC3000 EU), the DFC400 EU Marine is also developed for application on board large vessels, for auxiliary power generation. Fuel cells can supply safe and clean electricity to ships moored in ports and sailing coastal waters, in accordance to the ever more stringent environmental legislations governing the generation of on-board power and propulsion in the protected areas of Europe's coast line.

Moreover, FCES offers to their European customers:

- long-term service agreements: up to twenty years of protection with varying levels of support, depending on specific maintenance priorities and customer needs;
- on-line support: a dedicated web portal allows DFC® owners access to performance metrics for tracking and documenting performance and logistical support;
- preventative maintenance: regional service technicians and comprehensive warehousing support keep DFC® products operating as expected;
- refurbishment/recycling: as part of their environmental commitment, FCES will refurbish or recycle parts as appropriate, including fuel cell stacks at end-of-life.

Market perspectives

The aim of FCES is to penetrate further into the market in the European area and to leverage on the core technology to expand market opportunities. Because the power plants of FCES are an ultra-clean, efficient and reliable source for power, the German government adopted funding projects and supports the development of the technology to make it an attractive alternative to traditional power generation systems (see also section 2.3). The reduction of costs is an important goal of FCES which will be realized by a higher production volume and further product enhancements.

Franco Cell (France)

Company

The Franco Cell strategy is to become a reference in designing, building and running green base load stationary power units dedicated to locations isolated from the larger electricity network. Following extensive technology evaluation studies, Franco Cell decided to focus on green power generation solutions based on MCFC technology fuelled by sugar cane ethanol. The first project is a multi MW power plant construction in the French Caribbean based on advanced technology solutions including MCFC systems and additional cogeneration systems.

This project will be dedicated to base load electricity power generation. Due to its high thermal integration engineering, over 56% electrical efficiency is targeted. The Franco Cell business plan is to implement this technology in non-grid connected places with an objective of ten new power plants in the next ten years.

Located in the Paris area in France, Franco Cell has been funded in 2006 by private French investors aiming at developing a base load green solution that could compete with diesel power generation. Franco Cell identified island power generation with MCFC as a first niche market.
Company research thereby focused on three domains with the overall objective of reaching the best electrical efficiency:

- ethanol reforming for CH_4 production,
- thermal integration between MCFC exhaust and external reforming,
- system integration based on a three-way cogeneration solution.

Core products
Franco Cell conducted the preliminary feasibility studies on a multi-megawatt power plant project can be considered as one of the most advanced in the world considering its cogeneration architecture, level of power generated with hybrid fuel cells solutions, its CO_2 neutral feature, and the high energy efficiency that is expected to reach over 56%.
The power plant architecture is based on the co-exploitation of several standardized power cogeneration units located on the same site with common general infrastructure for fuel supply and storage, local grid interconnection and power plant management. A unit is, build on an original architecture comprising an external ethanol reformer with an associated turbine for outlet gas depressurization, a fuel cell system including an internal reformer, and an optional cogeneration Rankin cycle machine connected to the fuel cell exhaust. The gas depressurization turbine and the Rankine machine produce additional electricity combined with the stationary fuel cell generated power.
The external pre reformer is designed to produce a rich methane gas meeting the chemical input requirements of the MCFC technology. The process is based on steam reforming using dedicated catalyst formulations. The rich methane gas produced is used as the primary fuel to run the fuel cell system in a similar way as if it was running on land field gas. Due to the choice of an external ethanol pre-reformer, the use of ethanol fuel has very little impact on MCFC standard technology. In that case, most of the commercial MCFC solutions commercially available can be considered to be part of Franco Cell industrial solutions. Each standard tri-generation unit has a targeted power capacity close to 3.3 MW with 56% electricity efficiency. Combining several standard tri-generation units on the same plant location, Franco Cell power plants have the scalability to fulfil the local electricity demand and grid constraints. The electricity produced by each power unit is combined before being injected to the public local grid and is seen as a single power installation by the local public electricity grid management team.

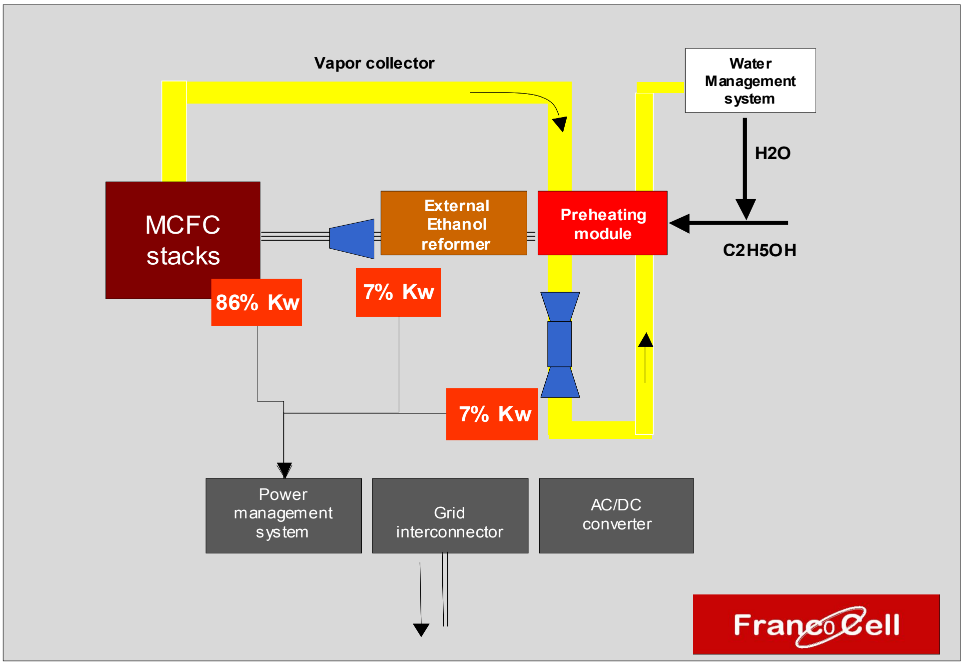

Figure 8 – The Franco Cell solution: a multimegawatt power unit with 56% electrical efficiency from ethanol as fuel and "zero" NOx, SO_2 and particulates [source: FrancoCell, presentation at IWMC 2012, Paris]

Market perspectives

This first power plant dedicated to island electricity production is planned to be deployed in three phases up to 30 MW, promoting green electricity Fuel Cell generation solutions as an alternate solution to diesel and other fossil fuel power units, according to the cycle described in Figure 9.

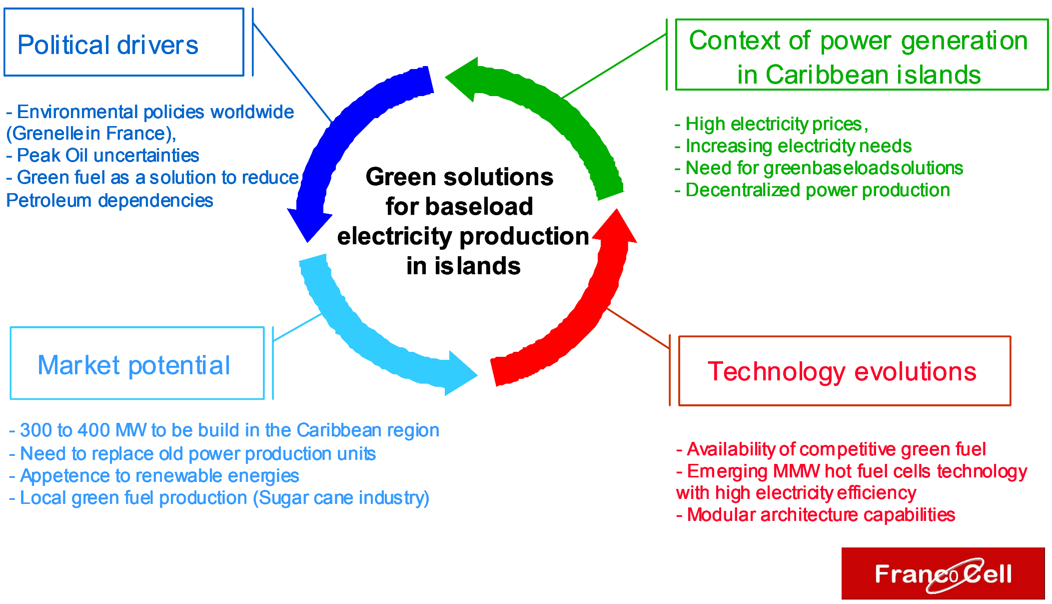

Figure 9 – How Franco Cell develops disruptive solutions to meet the new challenges of the electricity industry [source: Franco Cell, presentation at IWMC 2012, Paris]

2.3 MCFC Research and Development

ENEA (Italy)

The mission of ENEA's High-temperature fuel cells Operating and Testing Lab is to carry out advanced testing, characterization and evaluation of MCFC and SOFC components and systems, making use of cutting-edge experimental approaches and measurement techniques, for the benefit of industries and for the advancement of scientific knowledge in the field. ENEA has over 25 years' experience in the investigation and development of the MCFC, matured in collaboration with Ansaldo Fuel Cells before, then with FuelCell Energy Solutions, and always in close contact with the other research institutions listed here. Noteworthy is the Global Research Lab programme 2009-2015 with KIST which enabled to understand fundamental mechanisms of deactivation caused by harmful impurities and contaminants in CO_2-neutral fuels.

ENEA coordinated the European project MCFC-CONTEX, the largest European R&D project in MCFC of the last five years. The laboratory's specific activities currently consist in:

- Electrochemical characterization of materials, coatings and components,
- Advanced in-operando characterization of MCFC (cell and stack) performance through electrochemical impedance spectroscopy deconvolution and localized gas analysis,
- Experimental evaluation of complex fuels and fuel contaminant effects on MCFC and long-term durability,
- Experimental validation of accelerated and industrial testing procedures for objective MCFC characterization for several applications.

ENEA's High-temperature fuel cells Operating and Testing Lab, with its far-reaching national and international collaborations, is a point of reference in Italy and Europe as regards the realization and enabling of fuel cell deployment, through mediation between developers and customers, providing platforms for entrepreneurs and policymakers in the field, building awareness, exploring market opportunities and pointing out gaps in knowledge and regulation.

University of Perugia (Italy)

The University of Perugia's Fuel Cell Laboratory (FCLab) is part of the Engineering Department and focuses on high temperature fuel cell performance and characterization, µCHP, innovative fuels (biogas, syngas, ammonia, etc.), power production, carbon capture & storage (CCS), system integration and fuel treatment (clean up and reforming).

FCLab started to work on MCFC collaborating with Ansaldo Fuel Cells focusing on the use of MCFCs as power generators and in particular on behaviour under anodic sulphur poisoning, connected with natural gas or biogas fuelling. Over time, FCLab research themes moved to the innovative application of CCS that foresees retrofitting the MCFC to conventional engines, or any other carbon dioxide system producer, to separate the CO_2 before emission to atmosphere, exploiting the natural MCFC operating principle (see Chapter 3, section 3.1). With regard to this application FCLab focuses, with supplied materials, on SO_2 poisoning at the cathode side and on the study of MCFC behaviour in specific operating conditions such as the power or cement industry.

The activity on CCS was carried out in the frame of the European project MCFC-CONTEX. Industrial partnership is on-going in collaboration with FuelCell Energy Solutions.

University of Genoa (Italy)

The Process Engineering Research Team (PERT) of the Department of Civil, Chemical and Environmental Engineering specialises in chemical engineering, with specific interest in the interaction of technology and the environment for the promotion of sustainable ecological and human development. PERT has been involved for over 15 years in the theoretical study of fuel cells. Micro-modelling and flow distribution have been the subject of research and publications since the early 1990s. An effective modelling approach has been set-up at different degrees of detail, from laboratory-scale up to commercial power plant size, using commercial as well as self-developed codes. PERT research activity focuses on MCFC technology developing the optimized shape for planar cells (with an associated European Patent concerning MCFC performance optimization) as well as an elaborate 3D model, compiled in SIMFC (their in-house code), refined in detail in the last 4 years, that predicts MCFC performance in terms of electrochemical kinetics, thermal management, contaminant effects, operating point, and time-dependent degradation of given cell materials. This model was optimized within the framework of the MCFC-CONTEX project financed by the European Commission.

Fraunhofer-IKTS (Germany)

The Fraunhofer Insitute for Ceramic Technologies and Systems IKTS is the leading non-profit research institute for ceramic technologies in Europe. Within the “Energy” business unit, high-temperature fuel cells are one of the main pillars of R&D services covering the complete value chain from materials development and processing technologies towards system integration and prototype demonstration. MCFC activities were initiated in 2012 after adoption of assets and IP out of terminated MCFC developments at MTU and Tognum. Through a joint venture with Fuel Cell Energy, Inc. (USA), IKTS is involved in the Germany-based company Fuel Cell Energy Solutions GmbH (see section 2.2 above).

In July 2014 a collaborative, publicly funded R&D project was initiated, addressing material development and lifetime enhancements of state-of-the-art MCFC technology. The R&D project “MCFC-Next”, funded by German Federal Ministry of Science and Technology, governs the short-term MCFC activities at IKTS until 2017. Apart from intensified efforts for MCFC stack modelling and testing, the majority of R&D activities is focused on materials development, concentrated on addressing the following problems:

- Decreasing the solubility of matrix and cathode materials and reducing the particles growth in the carbonate melt with different additions,
- Investigation of the wetting behavior of molten carbonates depending on their temperature and composition,
- Quantitative understanding of molten electrolyte interaction with ceramic/metallic materials during the MCFC-operation.

Resolving these problems will contribute not only to extending MCFC lifetime, but also to further development of materials for high-temperature thermal and electrochemical energy storage systems, whose performance critically depends on the interaction between corrosive melt and ceramic/metallic materials.

Royal Institute of Technology, KTH (Sweden)

Work on high temperature fuel cells started in 1989 with research on MCFC. Ever since then, performance and modelling of the different components in the fuel cell have been in the focus of research. The group is well equipped with modern instruments for electrochemical experiments and there is a special MCFC laboratory equipped with two complete laboratory test rigs for fuel cells of 3 cm^2 geometric area and several ovens available for in-depth investigation of electrochemical processes, such as half-cell experiments, etc.

In the recent EU-financed project, MCFC-CONTEX, the performance and degradation of the MCFC used for CO_2 separation from combustion flue gas was studied. It was found that the presence of contaminating sulphur compounds such as SO_2 is of special interest in such applications, but also the low concentration of CO_2 in the flue gas when compared to cathode conditions in normal operation.

Recently the group has also investigated the feasibility of using the MCFC in reversible mode, i.e. to use the MCFC also for production of fuels by electrolysis. The performance in reversed mode is very promising, but further long-term tests are needed to demonstrate the viability of the concept.

Paris Institute of Research in Chemistry (France)

This team has a very large experience since the late eighties in the understanding of fundamental electrochemical phenomena and materials behaviour in order to optimise MCFC devices. The tools used in this activity comprise all the electrochemical characterisation techniques, several deposition techniques, structural/surface analysis and solution analysis. A set-up for single cell tests is being installed.

In 2014-2015, the main goals of this team are the following:

- Protection of the state-of-the art $Li_xNi_{1-x}O$ cathode from corrosion and dissolution with ultra-thin layers of few tenth of nm of TiO_2, CeO_2 or Co_3O_4 by a highly conformal technique, such as Atomic layer deposition (ALD), or by low cost techniques.
- The modification of the properties of the molten carbonate electrolyte by addition of caesium or rubidium ions favouring the reduction of oxygen. Thermodynamic and kinetic approaches are combined to understand the role of the additives and how they affect oxygen reduction.
- The use of new very promising hybrid electrolytes carbonates/solid oxides to improve MCFC operation. Knowing that the common support of the carbonate eutectics is $LiAlO_2$, which is responsible of 70% of the electrolyte ohmic drop, its replacement by the common solid oxide electrolyte, should greatly improve the global electrolyte behaviour.

- The team is also involved in the separation and valorisation of CO_2 in molten carbonate media. In particular, the feasibility of CO_2 electroreduction into CO has been proven theoretically and experimentally. Works is going on the process using cheap and optimised cathode materials.

The team is also involved in organising with other partners international workshops on MCFC and related topics, such as the IWMC (International Workshop on Molten Carbonates) series.

Warsaw University of Technology (Poland)

The Institute of Heat Engineering (IHE) at Warsaw University of Technology is located in Poland where they carry out the fuel cell development activities. The main target is to use MCFC as CO_2 reducer of coal fired power plant flue gases. IHE has validated several single cell (16-120 cm^2) laboratory scale units for natural gas, biogas and hydrogen. Since 2013 IHE possesses a 1 kW MCFC stack as well as mobile container for in-situ investigations.

IHE is also active in MCFC simulation, adopting new approaches for modeling cell voltage. Electrochemical, thermal, electrical and flow parameters are collected in a 0-D mathematical model, which rivals the classic approach. MCFC voltage is described by a few factors which have physical explanations: maximum voltage; fuel utilization factor; maximum current density; area specific internal ionic resistance; and area specific internal electric resistance. Thus, investigation of the specific component of the fuel cell (e.g. new electrolyte material, new catalyst layer, new fuel, etc.) should be related to the adequate factor listed; not for the whole current density-voltage curve as is currently practiced.

University of Connecticut (USA)

University of Connecticut (UConn), a premier research institution in the State of Connecticut, is conducting cutting edge research in MCFC technology in collaboration with federal agencies and industry partners. The research team at UConn is focused on (a) the development and validation of mechanistic understanding of various degradation processes associated with long term cell, stack and systems operation, (b) identification of degradation mitigation strategies and (c) experimental validation and implementation of degradation mitigation approaches in the MCFC systems.

University of Connecticut, through its Center for Clean Energy Engineering (C2E2), offers state of the art laboratory capabilities for long term electrochemical testing, advanced materials synthesis, in-situ and ex-situ characterization of active and inactive cell and stack components, and structural characterization of pre and post tested cell components. Active research areas include:

- Matrix materials stability evaluation and mechanisms
- Development of advanced matrix materials and salt chemistry
- High temperature wetting behavior of molten salt
- Liquid- solid-gas interactions and corrosion
- Oxide solubility in oxidizing and reducing atmospheres.

University of Connecticut works closely with FuelCell Energy and US Department of Energy. University of Connecticut, through its Fraunhofer Center for Energy innovation, also conducts research in advanced fuel cell systems.

KIST (South Korea)

The Fuel Cell Center of the Korean Institute of Science and Technology (KIST) has vast experience and capacity devoted to MCFC development, from fundamentals to application, matured since 1989. The KIST Fuel Cell Center in KIST has carried out many research projects in collaboration with many industrial companies such as Korean Electric Power Company (KEPCO), Doosan Heavy Industries & Construction (DHI), and POSCO Energy. Based on the technologies developed in these projects by Fuel Cell Center, several MCFC systems for demonstration were successfully operated. Fuel Cell Center in KIST has mainly focused on cell components and stack & system design. Early stage of MCFC development in Korea, Fuel Cell Center in KIST developed cell components fabrication processes for MCFC stack and these processes became the basis for the current components fabrication processes used in Korean stack developers. Also, Fuel Cell Center in KIST has developed new stack design and system to improve performance and efficiency of the MCFC system. Current focus looks at low-operating temperature MCFCs (550-580 °C) in order to ensure radically extended long-term operation (70,000 h). They have developed a high performance cathode which shows good electrochemical activities at around 550 °C.

From 2009 to 2015, the Global Research Lab Program between KIST and ENEA (Italy) looked deeply into structural effects on the active components for MCFCs running on alternative fuels and enabled the development of durable electrodes and cost-effective processes for cell fabrication, as well as harmonization of characterization test protocols.

In 2015 a new project is due to start on MCFC, entitled “Development of Core Components and Their Fabrication Methods for Durable MCFC Stacks”. In this project, a drastic revision of the basic MCFC component materials (matrix, anode, and separator material) is targeted.

3. The Versatility of MCFC Systems: New Applications

3.1 Carbon dioxide separation

To address the concerns about climate change resulting from the industrial emission of carbon dioxide (CO_2) in the shorter term, as a bridging solution towards a more sustainable CO_2-neutral energy infrastructure, Carbon Capture and Storage (CCS) is probably the most effective means to meet greenhouse gas emission mitigation objectives.

CCS technology can be divided into three main branches: post- and pre-combustion capture, and oxyfuel combustion. Oxyfuel combustion consists in the utilization of pure oxygen instead of air for combustion, which leaves an exhaust composed of only water and CO_2, which can be easily separated by e.g. condensation. Pre-combustion capture implies a three-step approach where fuel is gasified and transformed with the aid of steam to a mix of hydrogen (H_2) and CO_2, after which the latter is separated and a carbon free final combustion can take place. These two approaches are complex in nature and require appropriately designed plants, meaning that all existing and currently operating (and CO_2-emitting) conventional power plants cannot benefit from this kind of solution.

Post combustion capture is the only mature technology with a high readiness level: carbon dioxide is intercepted and separated from the flue gas as-is, before it is vented from the combustion-based power plant. The main technology adopted currently is a scrubbing process using MEA (Mono Ethanol Ammine) in a water solution. This technology has the great disadvantage of a high energy penalization: enormous volumes of exhaust gas have to be scrubbed (due to the strong dilution of CO_2 in nitrogen originated from the combustion air) and a significant part of the power plant's energy is lost in the MEA regeneration process. With a radically innovative approach, MCFCs could be used to separate the CO_2 from the flue gas instead, *generating* power in the process.

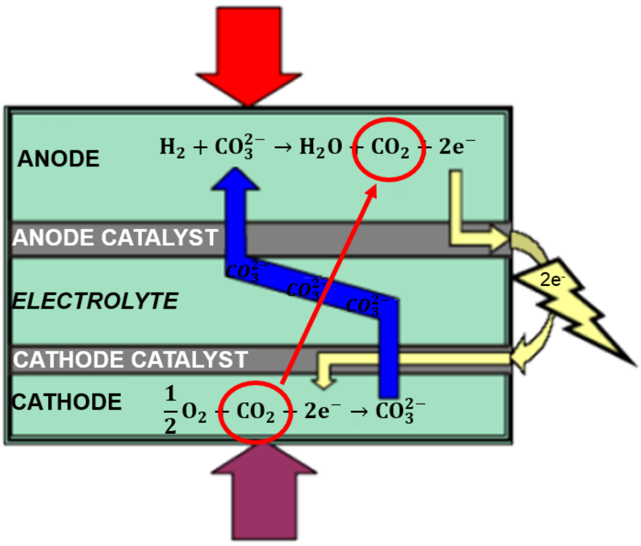

Figure 10 – The CO_2 transfer mechanism in a MCFC

As already mentioned in Chapter 1 (see section 1.1 and Figure 10), the MCFC can be used to separate CO_2 thanks to the functional reactions that occur inside the cell: $CO_3^{=}$ ions transport CO_2 directly from cathode side to the anode side. By sending flue gas (of a coal-fired power plant for example) to the cathode, the CO_2 will be selectively extracted and concentrated at the anode, in a mixture of water and small amounts of unreacted hydrogen and methane. The result is that the power plant flue gas will be expelled to the atmosphere with up to 70% less CO_2 content, which will have been transferred to the much smaller and concentrated MCFC anode exhaust stream from which it can be separated much more effectively, yielding a high-purity flow of CO_2. Above all, in this process *extra power* is generated, since the MCFC will be fuelled and operated normally to carry out the separation.

Using the MCFC as a CCS solution therefore presents a lot of advantages:

- Production of additional electric power, while separating CO_2 from flue gas, increasing the overall efficiency of the power plant
- Increased compactness of the post-combustion plant and reduced energy penalties for CCS
- The modularity feature of MCFC systems allows to gradually increase the size of capture device, tailoring it according to the actual capturing needs.

FuelCell Energy (see section 2.1) has already developed and patented (US Patent 7,396,603 B2) a system concept for greenhouse gas emission reduction based on this approach called Combined Electric Power and Carbon-dioxide Separation (CEPACS, see Figure 11). As explained, the concept's key feature is that the MCFC utilizes the CO_2 of the flue gas as a reactant for the electrochemical reaction to produce power, while synergistically transferring CO_2 from the flue gas to the anode exhaust stream. A supplementary fuel such as natural gas, biogas from a digester, or syngas from a biomass/coal gasifier is internally reformed in the fuel cell anode to provide the hydrogen needed to complete the electrochemical power generation cycle.

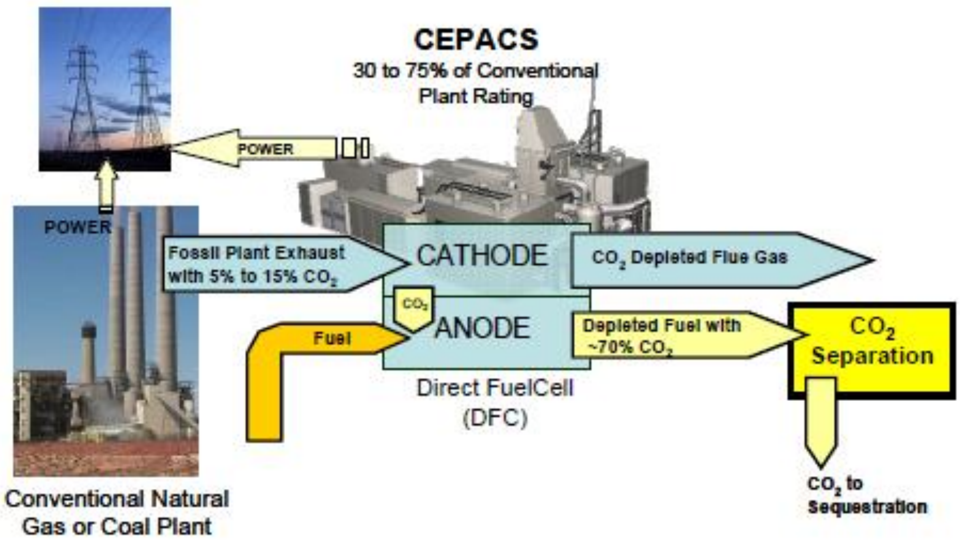

Figure 11 – The CEPACS configuration for active CO_2 separation from industrial flue gas [source: http://www3.aiche.org/proceedings/Abstract.aspx?PaperID=287935]

MEA-based scrubbing technology (MEA) is considered to be the state-of-the-art for separating CO_2. However, the energy and efficiency penalties of using ammines for CO_2 capture in combustion-based plants are substantial. About 22-30% of plant gross power is used up by the ammine system, reducing the plant efficiency to below 30%. Operation of a system such as CEPACS may instead result in an excess of 50% increase in net power output.

The incremental cost of electricity (COE) for the CEPACS technology applied to a pulverized coal combustion plant is compared with ammine-based scrubbing and oxyfuel combustion in Figure 12, showing that MCFC-based CO_2 capture is the only solution that has the potential to meet (and exceed) the US Department of Energy (DOE) goal of applying CCS with less than 35% increase in COE.

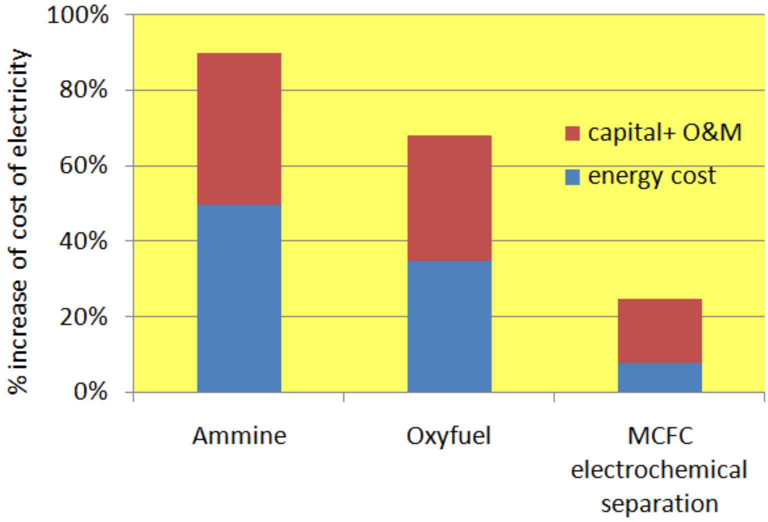

Figure 12 – Different CCS technologies compared in terms of the incremental cost of electricity produced by the combustion-based plant
[source: http://www3.aiche.org/proceedings/Abstract.aspx?PaperID=287935]

In August 2014 FuelCell Energy announced progression into stage three of the carbon capture development project supported by the DOE Office of Fossil Energy's Carbon Capture Program, and implemented by the National Energy Technology Laboratory. After achieving the project design and financial goals established for phases one and two, FuelCell Energy has received $1.2 million to continue into phase three of the project including the validation of the CO_2 capture process using a DFC fuel cell stack.

3.2 Hydrogen production

MCFC systems can also be employed as CHHP (Combined Heat, Hydrogen and Power) system. The idea behind this application is to recuperate unreacted hydrogen from the MCFC anode outlet (using appropriate adsorption or separation systems) in order to obtain pure hydrogen that can be compressed and stored. The rationale lies in the increased interest, world-wide, in using hydrogen

as an appropriate vector for storing excess renewable power and for grid stabilization, as well as providing a zero-local-emissions fuel for fuel cell electric vehicles.
In a scenario where renewable energy sources such as wind and solar will be exploited on a large scale (over 20% of final production) the fluctuating nature of these unpredictable sources becomes a major issue for a stable and reliable electricity supply. The great advantage of using the MCFC in CHHP configuration lies in the flexibility of the system, since the MCFC can be operated in part or full load without appreciable differences in net primary energy efficiency: being fed with natural gas or biogas, the amount of hydrogen coming out of the system is complementary to the power produced by the cell. This means that when the grid demands less electrical power (for example due to peaks in wind or solar electricity production) the CHHP system will be regulated to ramp down power production and thus make more hydrogen available at the exit of the cell, without loss in fuel efficiency. Such a configuration for MCFC can thus become a crucial integrating device for the regulation of smart grids and cities – see Figure 13.

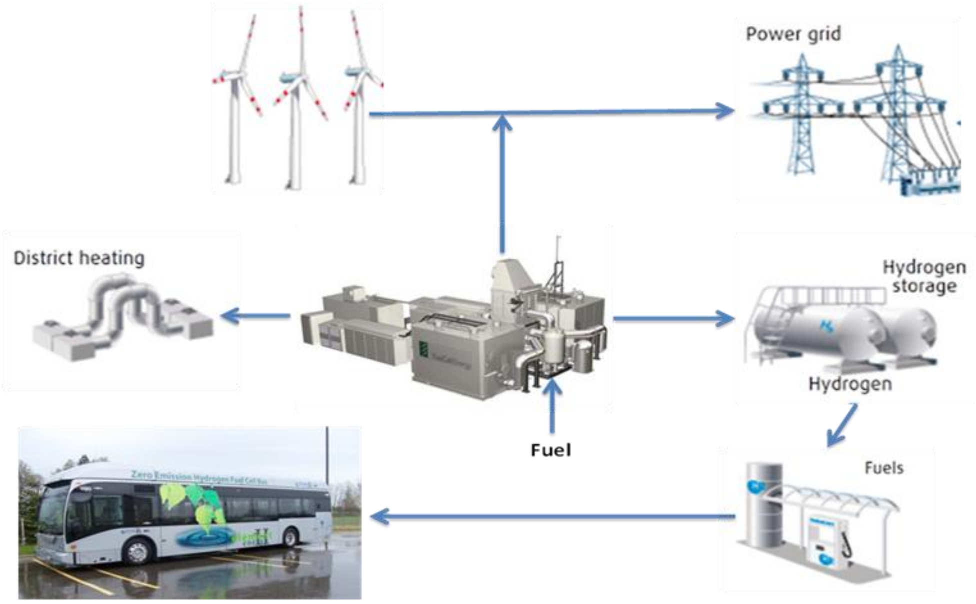

Figure 13 – How an MCFC system in CHHP configuration can contribute to a smart integration of energy supply and consumption [source: ENEA]

3.3 MCFC-microturbine coupling

Hybrid systems, fuel cells integrated with gas turbines, are based on the combination of the two technologies to achieve an overall higher efficiency for power generation.
For a high-temperature system such as the MCFC, different configurations can be adopted: with *indirect* coupling, the hot exhaust gases from the MCFC can be used as the heat source to run an externally heated turbine cycle (for example an Organic Rankine Cycle, ORC); with *direct* coupling, the MCFC is pressurized so that the exhaust gases (not completely depleted of combustibles) can

be sent to a combustion chamber for subsequent direct conversion of the expelled gases to power in an expansion turbine.

The two layouts, direct and indirect, are schematized in Figure 14, where the MCFC constitutes the topping system where fuel is added and the bottoming cycle recuperates mass and/or heat for further efficiency increase. The working fluids of the gas turbines in the direct and indirect configurations are a mixture of combustion gases in the former case, and hot air in the latter.

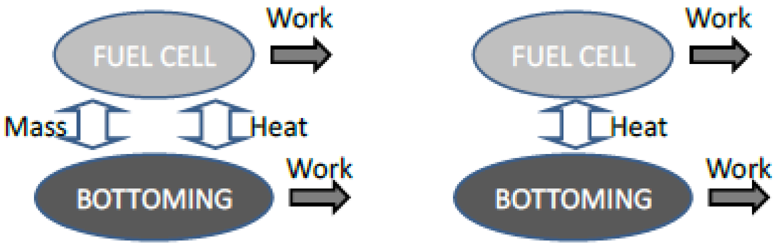

Figure 14 – How efficiency can be further increased through hybridization with an expansion (left) or recuperating (right) cycle [source: University of Seville]

The *direct* coupling of MCFC and gas turbines brings with it a lot of operational problems, particularly related to the matching of compressor/turbine and fuel cell operating regimes and reaction times, especially critical in transient operation. Using *indirect* hybridization the expansion turbine is coupled through a heat exchanger, which induces a more flexible system. A further benefit is that no further combustion takes place, avoiding the production of NO_x in the bottoming cycle.

With optimized integration, overall electrical efficiencies can be achieved of over 60%, which is unique for the sub-GW scale for which these systems can be designed.

4. Contact List for MCFC Deployment

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