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VLEEM 2

EC/DG Research
Contract ENG1-CT 2002-00645

FINAL REPORT

ANNEX 3.32:
High-temperature fuel cell systems

P. Lako

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1. INTRODUCTION

This report addresses the long-term potential of high-temperature fuel cell systems. High-temperature fuel cell systems may be used for Combined Heat and Power (CHP) or for high-efficiency power generation. In this study, the focus is on the application of high-temperature fuel cell systems for industrial CHP.

High-temperature fuel cell systems are in the stage of research, development, and demonstration (RD&D). Before these fuel cell systems may be considered commercial, several barriers will have to be surmounted. Table 1.1 gives an overview of barriers, challenges, and open questions regarding stationary fuel cells (Pehnt, 2004).

Table 1.1 *Potential barriers/open questions regarding fuel cells in stationary applications*

Energy Economic, Legal • Capital cost • Future demand, such as reduced heat demand • Structural changes in traditional heating markets • International codes, standards and safety regulation • Unfavourable conditions for competition with established generation (no level playing field, aggressive price dumping, etc.) • Institutional/regulatory barriers to market access, e.g. in terms of backup power	Customer, Installation and Marketing • Investors waiting • Complexity of technology and interactions with electricity demands one-stop solutions • Customer acceptance of new technologies and distribution channels (e.g. contracting) • Installation personnel: cooperation of craftsmen of different trades, etc. • Qualification and training demand. • Transaction costs for systems integration (e.g. as virtual power plant) • Insufficient integral planning of energy supply/demand of objects, buildings, settlements, communities
Technical • Lifetime of stack, degradation • Reliability and compatibility of balance of plant components • Achieving target electric efficiencies • Thermal efficiencies • Availability of Balance-of-Plant components • Technical aspects of grid connection	Miscellaneous • Time gap between Kyoto CO_2 reduction and readiness for market • Danger of over-heated euphoria, little tolerance to initial start-up problems Further barriers common to all CHP systems, such as: • Interconnection issues and grid access • Heat distribution

Source: Pehnt, 2004.

The issues addressed in this report are mainly those in the ‘Technical quadrant’ and the capital cost in the quadrant ‘Energy Economic, Legal’. Therefore, a lot of issues are not regarded.

Chapter 2 focuses on the option of the Molten Carbonate Fuel Cell (MCFC) system, a well-known high-temperature fuel cell system. Chapter 3 addresses the Solid Oxide Fuel Cell (SOFC) system, the other high-temperature fuel cell system that is currently developed. Chapter 4 contains a number of conclusions based on the analysis presented in this report.

2. MOLTEN CARBONATE FUEL CELL SYSTEMS

2.1 Introduction

The Molten Carbonate Fuel Cell (MCFC) system is one of the two high-temperature fuel cell systems that is analysed in this report. In the following, the current status (§2.2) and the potential of MCFC fuel cell systems (§2.3) for industrial CHP are addressed.

2.2 Current status

In an MCFC, the electrolyte is a mixture of lithium and potassium carbonate salts that melt at the operating temperature of 650 ºC (Krewitt, 2004). The electrolyte conducts carbonate ions (CO_3^{2-}) from the porous NiO-cathode to the porous Ni-anode where they react with hydrogen to form water and carbon dioxide. The CO_3^{2-} ions are replenished by reacting oxygen with carbon dioxide recycled from the anode. A CO_2 gas recycling system is needed to supply CO_2 from the anode chamber to the cathode chamber. The electrochemical reactions occurring in MCFCs can be summarised as follows:

Anode: $2H_2 + 2CO_3^{2-}$ => $2H_2O + 2CO_2 + 4\ e-$
Cathode: $O_2 + 2CO_2 + 4\ e-$ => $2CO_3^{2-}$
Overall cell reaction: $2H_2 + O_2 + 2CO_2$ (cathode) => $2H_2O + 2CO_2$ (anode)

At 650 ºC, methane is internally reformed at the anode promoted by a catalyst (Internet source 1). Various concepts have been developed for natural gas, coal gas, biogas etc. as a fuel. Table 2.1 presents the state-of-the-art of the MCFC (Krewitt, 2004; Gnann, 2003; Powell, 2004).

Table 2.1 *Current status of stationary Molten Carbonate Fuel Cell (MCFC) systems*

Parameter	Unit	State-of-the-art 2004
Operating temperature	[ºC]	~ 650
Internal/external reforming		Internal
Electrolyte		Molten Carbonate Salt
Oxidant		CO_2/O_2/air
Capacity	[kW$_e$]	250 - 3,000
Availability	[%]	~ 80
Electrical efficiency	[%]	47
Thermal efficiency (10 bar steam)	[%]	16
Total efficiency	[%]	63
Lifetime of fuel cell stacks	[hr]	40,000
Envisioned start of series production	[year]	2006
Specific investment cost	[/kW$_e$]	8,000-12,000
Operation and maintenance cost	[/kW$_e$/a]	200-300

Sources: Krewitt, 2004; Gnann, 2003; Powell, 2004.

MTU expects that series production of their (250 kW$_e$) MCFC systems is to begin in 2006, and from 2007 onwards there will be some 100 systems produced per annum (Internet source 2).

2.3 Potential for industrial CHP

Currently, CHP based on high-temperature fuel cell systems is not financially competitive compared with conventional systems. However this could change if, for example, the lifetime of fuel cell stacks increased and the capital costs reduced. Lower local emissions and reliable and quiet operating performance could also be an advantage (Powell, 2004). It is assumed that the performance and cost of future MCFC systems will be improved by incremental improvements and step-changes. Table 2.2 shows the anticipated improvements in the period 2010-2030.

Table 2.2 *Estimates of performance and cost data of stationary MCFC systems*

Parameter	Unit	Year 2010	Year 2020	Year 2030
Availability	[%]	85	90	95
Electrical efficiency	[%]	52	52	52
Thermal efficiency (10 bar steam)	[%]	16	16	16
Total efficiency	[%]	68	68	68
Lifetime of fuel cell stacks	[hr]	60,000	80,000	100,000
Specific investment cost	[/kW$_e$]	3,000	1,550	1,300
Operation and maintenance cost	[/kW$_e$/a]	100	75	50

The availability of MCFC systems is assumed to increase to 85% in 2010 and 7 95% in 2030. Likewise, the electrical efficiency is assumed to increase to 52%, whereas the thermal efficiency (steam, 10 bar) is assumed to remain 16% (Au, 2003). The lifetime of the fuel cell stacks might be increased to 60,000 hours in 2010, and 100,000 hours in 2030. System lifetime targets are 100,000 hours for large stationary power applications (Powell, 2004).

The cost estimates of future MCFC systems range from \$1,300 to \$1,800/kW$_e$ (Williams, 1999; Rastler, 2002). It is assumed that the specific investment cost of MCFC systems will come down to 3,000/kW$_e$ in 2010, 1,550/kW$_e$ in 2020, and 1,300/kW$_e$ in 2030. Figure 2.1 illustrates the possible reduction of the specific investment cost of MCFCs.

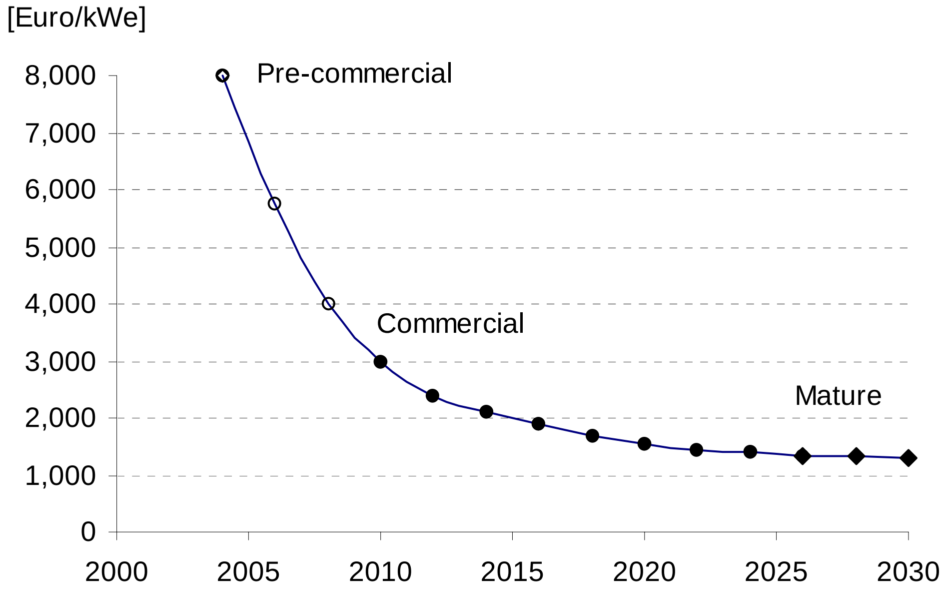

Figure 2. 1 *Anticipated cost reduction of MCFC systems, 2004-2030*

It has been assumed that MCFC systems for industrial CHP will become commercial around 2010. MCFC systems may capture commercial niche markets from 2005. The period of commercialisation is comparable to that of Phosphoric Acid Fuel Cell (PAFC) systems in the past decade. From 2004 and 2030, the specific investment cost is assumed to decrease by a factor of six to nine, due to technological learning (incremental technological improvements as well as step-changes). Assuming that MCFC systems have a so-called Progress Ratio of 0.8 - tantamount to a cost reduction of 20% for each doubling of the cumulative installed capacity - this would require between 8 and 10 doublings of the cumulative installed capacity until 2030.

3. SOLID OXIDE FUEL CELL SYSTEMS

3.1 Introduction

The Solid Oxide Fuel Cell (SOFC) system is another high-temperature fuel cell systems that is analysed in this report. In the following, the current status (§3.2) and the potential of SOFC fuel cell systems (§3.3) for industrial CHP are addressed.

3.2 Current status

SOFC do not comprise a liquid electrolyte with its attendant specific corrosion and electrolyte management problems. The operating temperature of > 800 ºC allows internal reforming, promotes rapid kinetics with non-precious materials, and produces as a high quality by-product high temperature heat. The high temperature of the SOFC, however, places stringent requirements on its materials, both with regard to the stack and the balance of plant components. The development of suitable low cost materials and the low cost fabrication of ceramic structures are presently the key technical challenges facing SOFC systems (Krewitt, 2004).

The SOFC cell consists of a solid ceramic electrolyte (yttria stabilised ZrO_2) pressed between a Ni/ZrO_2 cermet anode (usually stabilised with Y_2O_3) and a strontium-doped lanthanum manganite cathode. The ionic conduction in SOFCs is by oxygen ions. Carbon monoxide (CO) and hydrocarbons such as methane can be used as fuels in SOFC systems. The electrochemical reactions occurring in SOFCs can be summarised as follows (Internet source 3):

Anode: $2H_2 + 2O^{2-} \Rightarrow 2H_2O + 4\ e^-$
Cathode: $O_2 + 4\ e^- \Rightarrow 2O^{2-}$
Overall Cell Reaction: $2H_2 + O_2 \Rightarrow 2H_2O$

Basically, two design types are pursued, the tubular and the planar design type, each with different characteristics (Pålsson, 2002). Internal steam reforming of methane can take place in the SOFC thanks to the high operating temperature (> 800 ºC). This can be accomplished indirectly in separate reforming chambers in heat contact with the fuel cells (indirect internal reforming) or directly in the anode chambers (direct internal reforming). Table 3.1 presents the state-of-the-art of the SOFC (Krewitt, 2004; Vora, 2004; Powell, 2004).

Table 3.1 *Current status of stationary Solid Oxide Fuel Cell (SOFC) systems*

Parameter	Unit	State-of-the-art 2004
Operating temperature	[ºC]	> 800
Internal/external reforming		Internal
Electrolyte		Ceramic
Oxidant		O_2/air
Capacity	[kW$_e$]	250
Availability	[%]	~ 85
Electrical efficiency	[%]	46
Thermal efficiency (10 bar steam)	[%]	25
Total efficiency	[%]	71
Lifetime of fuel cell stacks	[hr]	60,000
Envisioned start of series production	[year]	2006
Specific investment cost	[/kW$_e$]	10,000
Operation and maintenance cost	[/kW$_e$/a]	250

Sources: Krewitt, 2004; Vora, 2004; Powell, 2004.

Siemens, currently the main supplier of SOFC systems, could produce (small) series of SOFCs within a few years. Also, the capacity and the availability of SOFC systems may be increased. According to (Baron, 2004), a recent collaboration of ETH Zürich, EMPA, Sulzer Innotec and EPFL (Switzerland), aiming at developing an anode supported SOFC using low-cost techniques, has achieved an electrical efficiency greater than 60% at a fuel utilisation of 90%. Also, the lifetime of the SOFC fuel cell stacks may be increased further.

3.3 Potential

Table 3.2 shows the anticipated characteristics of SOFC systems in the period 2010-2030.

Table 3.2 *Estimates of performance and cost data of stationary SOFC systems*

Parameter	Unit	Year 2010	Year 2020	Year 2030
Availability	[%]	90	95	7 95
Electrical efficiency	[%]	52	55	57
Thermal efficiency (10 bar steam)	[%]	25	25	25
Total efficiency	[%]	77	80	82
Lifetime of fuel cell stacks	[hr]	80,000	100,000	100,000
Specific investment cost	[/kW$_e$]	3,500	1,300	1,200
Operation and maintenance cost	[/kW$_e$/a]	120	75	50

The availability may be increased to 90% in 2010 and 7 95% in 2030. The electrical efficiency is assumed to increase to 57% in 2030, whereas the thermal efficiency (steam) is assumed to remain 25%. The lifetime of the fuel cell stacks might be increased to 100,000 hours.

The cost estimates of future SOFC systems range from \$1,000 to \$1,320/kW$_e$[1] (Vora, 2004; Pålsson, 2002). It is assumed that the specific investment cost of SOFC systems will come down to 3,500/kW$_e$ in 2010, 1,300/kW$_e$ in 2020, and 1,200/kW$_e$ in 2030. Figure 3.1 illustrates the possible reduction of the specific investment cost of SOFCs.

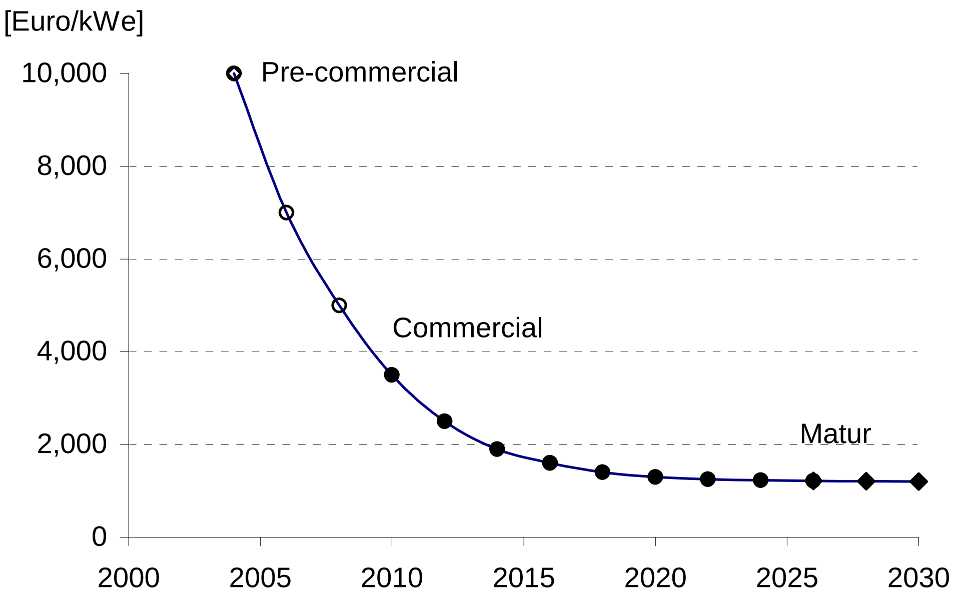

Figure 3. 1 *Anticipated cost reduction of SOFC systems, 2004-2030*

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[1] The cost estimate of \$1,320/kW pertains to a study of a 300 MW$_e$ combined SOFC gas turbine power plant. This study was performed under a contract with the Institute of Applied Energy in Japan (Pålsson, 2002).

It has been assumed that SOFC systems for industrial CHP will become commercial around 2010. SOFC systems may capture commercial niche markets from 2005. The period of commercialisation is comparable to that of Phosphoric Acid Fuel Cell (PAFC) systems in the past decade. From 2004 and 2030, the specific investment cost is assumed to decrease by a factor of approximately eight, due to technological learning (incremental technological improvements as well as step-changes). Assuming that SOFC systems have a so-called Progress Ratio of 0.8 - a cost reduction of 20% for each doubling of the cumulative installed capacity - this would require between 9 and 10 doublings of the cumulative installed capacity until 2030.

4. CONCLUSIONS

This report addresses the long-term potential of high-temperature fuel cell systems, and particularly on applications for industrial CHP. High-temperature fuel cell systems are in the stage of research, development, and demonstration (RD&D). Before these fuel cell systems may be considered commercial, several barriers will have to be surmounted. Technical improvements, both incremental improvements and step-changes, are needed to create commercial high-temperature fuel cell concepts.

With regard to MCFC fuel cell systems, the main conclusion is that MCFCs for industrial CHP may become commercially available around 2010, the electrical efficiency may be increased to 52% in 2010 with a thermal efficiency (steam) of 16%, and the specific investment cost may come down to an estimated 3,000/kW$_e$ in 2010, 1,550/kW$_e$ in 2020, and 1,300/kW$_e$ in 2030. This would require between 8 and 10 doublings of the cumulative installed capacity until 2030, presumed that MCFC systems have a so-called Progress Ratio of 0.8 - tantamount to a cost reduction of 20% for each doubling of the cumulative installed capacity.

For SOFC systems more or less comparable technological improvements and cost reductions may be achieved in the next twenty-five years. SOFC fuel cell systems for industrial CHP may become commercially available around 2010. The electrical efficiency may be increased to 52% in 2010 and 57% in 2030 with a thermal efficiency (steam) of 25%. The specific investment cost of SOFC systems may come down to an estimated 3,500/kW$_e$ in 2010, 1,300/kW$_e$ in 2020, and 1,200/kW$_e$ in 2030. This would require between 9 and 10 doublings of the cumulative installed capacity until 2030, based on a Progress Ratio for SOFC systems of 0.8.

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