Prospects for advanced coal-fuelled fuel cell power plants

D. Jansen*, P.C. van der Laag, A.B.J. Oudhuis and J.S. Ribberink
Netherlands Energy Research Foundation ECN, Business Unit Fossil Fuels, PO Box 1, 1755 ZG Petten (Netherlands)

Abstract

As part of ECN's in-house R and D programmes on clean energy conversion systems with high efficiencies and low emissions, system assessment studies have been carried out on coal gasification power plants integrated with high-temperature fuel cells (IGFC). The studies also included the potential to reduce CO_2 emissions, and to find possible ways for CO_2 extraction and sequestration. The development of this new type of clean coal technology for large-scale power generation is still far off. A significant market share is not envisaged before the year 2015. To assess the future market potential of coal-fuelled fuel cell power plants, the promise of this fuel cell technology was assessed against the performance and the development of current state-of-the-art large-scale power generation systems, namely the pulverized coal-fired power plants and the integrated coal gasification combined cycle (IGCC) power plants. With the anticipated progress in gas turbine and gas clean-up technology, coal-fuelled fuel cell power plants will have to face severe competition from advanced IGCC power plants, despite their higher efficiency.

1. Introduction

The effects of coal utilization on the environment are today of significant public concern. This concern has given rise to increasingly stringent environmental legislation in all developed countries. In spite of this, coal-based power generation has shown a continuous and steady growth. This is due to the abundance of the global coal resources, their geographical dispersion, and the relatively low price for extraction, transportation and conversion.

The demands for reduction of the environmental impact of coal-based power generation have been so far met by the introduction of appropriate cleaning techniques and the development of new clean coal technologies with high efficiencies and low emissions. The potential economic and environmental advantages of power production based on coal gasification are recognized, since a number of commercial integrated coal gasification combined cycle (IGCC) projects have been started during recent years.

As part of ECN's in-house R&D programmes on clean energy conversion systems with high efficiencies and low emissions [1], system assessment studies have been carried out on coal gasification power plants integrated with combustion turbines (IGCC) or high temperature fuel cells (IGFC). The studies included the potential to reduce the CO_2 emissions and to find possible ways for CO_2 recovery and sequestration. The main objectives of these assessment studies are the identification of system configurations which will result in competitive electricity production costs and iden-

*Author to whom correspondence should be addressed.

0378-7753/94/$07.00
SSDI 0378-7753(93)01807-T

tification of those parts of advanced coal-fuelled fuel cell power plants which are critical to system viability. This will help to determine priorities in our molten carbonate fuel cell (MCFC) R&D programmes.

2. Coal gasification

All the fuel cell systems being developed require hydrogen as their principal source of energy. There are no fuel cell systems possible that might produce electricity differently from coal. However, MCFCs and solid oxide fuel cells (SOFCs) are able to produce *in situ* hydrogen by reforming methane within the cell.

For low-temperature fuel cells CO is a poison, but high-temperature fuel cells (HTFCs) are able to produce power from the CO either directly by the oxidation of CO or indirectly via the water-gas-shift reaction. In high-temperature fuel cells CO is always accompanied by water and the apparent direct oxidation of CO occurs under conditions that favour the oxidation via shift conversion.

In coal-fuelled fuel cell power plants the conversion of coal either into hydrogen-rich fuel gas or into a fuel gas which can be readily reformed into hydrogen is an essential step. The coal conversion step, i.e., gasification, must be followed by a cleaning step to remove impurities from the coal-derived gases that will damage the fuel cell or other equipment. This cleaning step must be sufficient to meet environmental regulations.

2.1. Coal gasification for IGCC systems

Gasification of coal is a long-established technology, which has undergone substantial developments over the last twenty years. The aim of the gasification processes is to produce a high yield of gas in an environmentally benign manner. The first developments were aimed at the production of synthesis gas for use as chemical feedstock. The gasification technologies which are being most vigorously developed today are those which offer the most attractive route to clean, economic generation of electricity from coal. In these systems the gasifier is integrated with a combined cycle (steam and gas turbine).

For the IGCC application, several proprietary gasification processes have been developed, all of which have different features and consequently different comparative benefits. Companies involved include Shell, Texaco, DOW, Prenflo, HT-Winkler and British Gas/Lurgi. These gasification processes operate at pressures well above the gas turbine fuel system requirements and at high temperatures (1200–1600 °C). These so-called slagging gasifiers produce a vitreous slag which has been qualified as non-hazardous waste and can be used in the construction and highway industries. Table 1 gives the main characteristics of different gasification processes currently under development of IGCC application.

Coal can be gasified with steam either air or oxygen, creating two different kinds of fuel. Air-blown gasifiers produce a fuel gas with a low heating value, approximately one-ninth of that of natural gas. Oxygen-blown gasifiers produce a fuel gas of about one-fourth heating value of natural gas. Recent progress and evaluation of both costs and technology have generally resulted in the conclusion that gasification using oxygen is the most cost-effective and operable approach for IGCC systems.

The different gasification processes, with different types of coal-feed (dry or wet) and either air-blown or oxygen-blown operation, result in a range of fuel gas compositions relevant for the efficiency of the fuel cell. The efficiency of the fuel cell is adversely

TABLE 1

Gasification efficiencies for different gasification processes

Gasification process	Type	Feed	Oxidant system	Efficiency[a]
British Gas/Lurgi	Fixed-bed	Dry	Oxygen	92
DOW	Entrained-bed	Slurry	Oxygen	74
Prenflo/Shell	Entrained-bed	Dry	Oxygen	81
Texaco	Entrained-bed	Slurry	Oxygen	74
HT-Winkler	Fluidized-bed	Dry	Air	88

[a]Efficiency = LHV coal gas/LHV coal

TABLE 2

Coal gas compositions (before acid gas removal) of different oxygen-blown gasification processes

Compound (vol.%)	DOW	Prenflo	Shell	Texaco	BGL
CO	35	62	62	47	58
CO_2	25	4	2	15	2
H_2	38	27	29	35	28
H_2O	0.1	0.2	0.2	0.2	0.2
N_2+Ar	1	6	5	2	5
CH_4	0.04	0.01	0.01	0.06	6
S	0.2	0.7	0.9	0.3	0.2

affected by dilution of its fuel. The more dilute the fuel, the lower the maximum voltage of the cell and the greater the polarization losses at a given current density. Therefore, oxygen-blown gasification processes are more suitable for integration with fuel cells than air-blown gasification processes. The fuel gas should however contain a certain amount of CO_2 and/or water to avoid carbon formation in the fuel cell via the Boudouard reaction. The fuel gas compositions for the different oxygen-blown gasification processes are summarized in Table 2.

The demands of the HTFCs on the gasifier differ from those of gas turbines. The overall efficiency of an IGFC system appears to be more sensitive than that of an IGCC system to both fuel gas composition and purity, and to the conversion efficiency of the gasifier, i.e., to the efficiency of conversion to coal into chemical energy.

2.2. Advanced coal gasification

When considering gasification technologies suitable for integration with fuel cells, a wider range of gasification processes than those evaluated for IGCC applications appears to be of interest. In particular, advanced gasification processes that operate at the same temperature level as HTFCs, i.e., 600–1000 °C, are attractive [2]. However, from an environmental point of view these processes may be unacceptable in certain countries due to the leachability of the product ash.

Several of advanced gasification processes were developed and tested on pilot-plant scale in the 1970s to produce syngas with a high methane content to replace natural gas. These gasification processes all operate at conditions favouring methanation and perform best with a hydrogen recycle to the gasifier. In order to have acceptable reaction rates catalysts are often used. Exxon, for example, developed a catalytic fluidized bed gasification process in the 1970s which operates at about 700 °C and 50 bar. To accelerate the reactions, coal is impregnated with a K_2CO_3 catalyst. The coal is gasified with steam mixed with recycled synthesis gas. The major products are CH_4, CO_2, recycled CO and H_2 and unconverted steam. After cooling, CH_4 is separated from the fuel gas.

3. Gas purification

The raw coal-derived gas contains several impurities with levels exceeding the tolerances of either a combined cycle or a fuel cell system. Therefore a gas-cleaning system is required. Based on studies and experiments it is clear that the gas-cleaning requirements for coal-fuelled fuel cells are far more stringent than for other applications of coal gasification, such as the IGCC.

IGCC power generation plants such as that currently under construction in Buggenum, The Netherlands, use a wet process for cleaning raw coal-derived gas. Table 3 summarizes the impurity levels after the Buggenum clean-up system. Impurity levels of other trace components are not known.

Known MCFC tolerances for certain impurities commonly found in raw, coal-derived gases are summarized in Table 4. The long-term effects of some of these trace contaminants still require assessment, but some effects which are already known are discussed below.

3.1. Sulphur compounds

Sulphur is present as H_2S, COS, CS_2 and as SO_2 in the oxidant supply. When sulphur enters the MCFC anode of the fuel cell, it adheres to the catalytic nickel surface, reducing anode activity, in a reversible process. When sulphur dioxide enters the cathode of the MCFC it dissolves in the electrolyte and migrates to the anode, where it collects. This is an irreversible process. The sulphur tolerance of the SOFC and the MCFC are comparable. Following initial wet desulphurization used in IGCC systems, a more thorough cleaning of the fuel gas is required for IGFC systems. An activated zinc oxide bed has been found to be sufficient to clean the gas adequately (Haldor Topsoe Inc). Others suggest the use of an initial hot gas clean-up (zinc titanate) followed by a zinc oxide bed for final polishing.

TABLE 3

Impurity levels expected in coal gas, after the wet, low-temperature SULFINOL gas clean-up section at Buggenum, The Netherlands

Compound	Concentration (ppm)
H_2S	5
COS	15
HCl	<0.1
HF	<0.1
CH_4	100

TABLE 4

MCFC tolerances for different impurities in the fuel gas

Compound	Tolerance (literature)
H_2S (ppm)	1
SO_2	sub-ppm
HCl (ppm)	0.1
HF (ppm)	0.1
NH_3 (vol.%)	1
NO_x (vol.%)	1
Zn (ppm)	5
As (ppm)	1
H_2Se (ppm)	0.5
Particles (ppmw)	10

3.2. Ammonia

Wet-cleaning processes almost completely remove ammonia. In this case no additional polishing step is necessary. With hot-gas cleaning processes ammonia is not removed. However, the MCFC appears to be unaffected by ammonia at the anode. The combustion products of ammonia may give problems at the cathode of the MCFC.

Ammonia does not appear to have any effect on SOFCs.

3.3. Halogens

Halogen compounds, mainly HCl and HF, react with carbonate in the anode of the MCFC to form potassium salts in the vapour phase, changing the potassium/ lithium contents of the electrolyte melt. It has been reported that in high concentrations (>100 ppm) halogens may cause structural changes in SOFC. With wet-cleaning processes the halogen compounds are removed adequately as can be seen from Tables 3 and 4. No additional cleaning step seems to be needed.

When hot-gas clean-up processes are used, halogens must be removed in a separate step before desulphurization. The following compounds seem to be potential candidates for high-temperature HCl/HF removal: activated carbon, NaOH, Na_2CO_3, KOH, and $Ca(OH)_2$.

3.4. Particulates

The literature indicates that particulates (dust) have a negative effect on the fuel cell performance, since they plug porous components. Typical tolerances are diameter, $d < 10$ μm.

3.5. Other trace compounds

Metal vapours and other trace components can have negative effects on the fuel cell performance, e.g., as follows:

(i) zinc: precipitation at the cell outlet, plugging of the anode pores with performance loss;

(ii) arsenic: absorption in electrolyte, with the formation of NiAs and deactivation of the anode;

(iii) H_2Se: reacts like H_2S, i.e., $H_2Se + Ni \leftrightarrow NiSe + H_2$;

(iv) other metal vapours: Cd, Sn, Hg have higher tolerance levels; there are no data available on negative long-term effects, and

(v) hydrocarbons: soot formation, plugging of fuel channels.

4. Integrated coal gasification fuel cell power plants

Assessments studies have been conducted in several countries over the last ten years to optimise the efficiency of integrated coal-gasification fuel cell (IGFC) power generation systems. The first studies were based on the use of phosphoric acid fuel cells (PAFCs) with coal gasifiers. Due to the low operating temperature of PAFCs, the possibility of increasing efficiency by adding a steam bottoming cycle was limited. HTFCs reject heat at temperatures suitable for raising high-quality steam for electricity generation in a bottoming cycle. To ensure high efficiencies, the bottoming cycle should have a minimum capacity of 100 MW_e, making steam reheat a feasible option.

4.1. Coal-fuelled molten carbonate fuel cell systems

The most straightforward design for IGFC systems is simply to replace the gas turbine in an IGCC system with a high-temperature fuel cell. Recently, in screening evaluations, ECN studied the combination of coal gasification with molten carbonate fuel cells (IGMCFC) [3, 4]. The goal of these screening evaluations was to determine the basis system configuration of IGMCFC cycles based on entrained bed gasification processes, i.e., Shell or Texaco gasification processes. The entrained bed gasification processes were chosen because these will be used in The Netherlands for future power generation plants.

Two main IGMCFC system configurations are evaluated:

(i) an IGMCFC cycle with a low-temperature gas clean-up subsystem (LTGC);

(ii) an IGMCFC cycle with a high-temperature gas clean-up subsystem (HTGC).

IGMCFC cycle with a low-temperature gas clean-up subsystem

In Fig. 1 the system configuration of a state-of-the-art IGMCFC power generation plant is given. The basic subsystems that can be distinguished are: the gasifier/syngas cooler together with the low-pressure air separation unit, the low-temperature gas clean-up section (LTGC) and the power production system (MCFC stacks and the heat recovery steam generation section (HRSG)). To lower the fuel gas pressure to the desired inlet pressure of the fuel cell stacks, expanders are used for generating additional electricity.

IGMCFC cycle with a high-temperature gas clean-up subsystem

One of the possible ways to increase the efficiency of IGMCFC power generation systems is the use of a high-temperature gas clean-up subsystem (HTGC). Assessment studies showed that, if successfully developed, the use of HTGC in IGCC power generation plants based on entrained bed gasification processes will increase efficiency by 2 to 3% points [5]. Therefore, an IGMCFC system with HTGC was also part of the screening evaluation.

In Fig. 2 the system configuration of this IGMCFC power generation plant with HTGC is given. Again three basic subsystems can be distinguished: the gasifier/syngas cooler together with the air separation unit, the gas clean-up subsystem and the power production section.

The gasifier/syngas cooler, the air separation unit and the MCFC are the same as those used in the IGMCFC power plant with LTGC, described above. The only

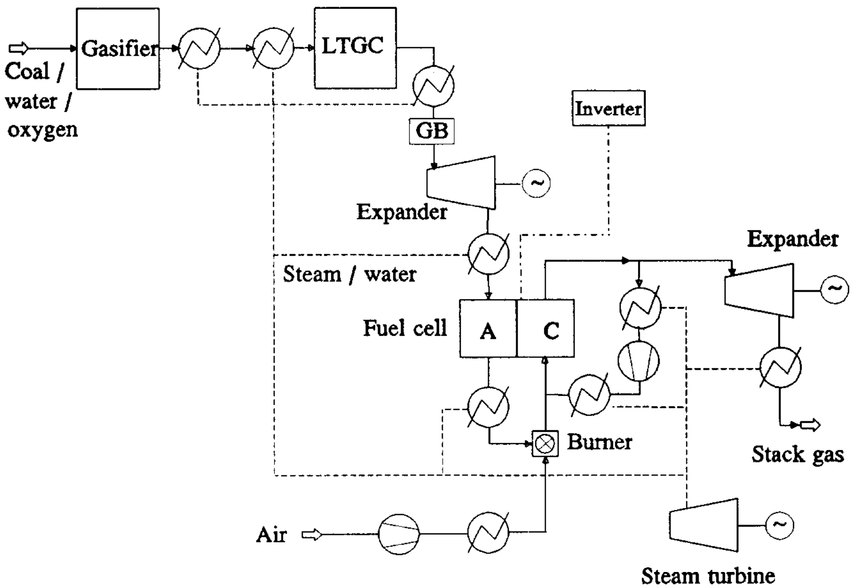

Fig. 1. Block diagram of an IGMCFC power plant with low-temperature gas clean-up equipment.

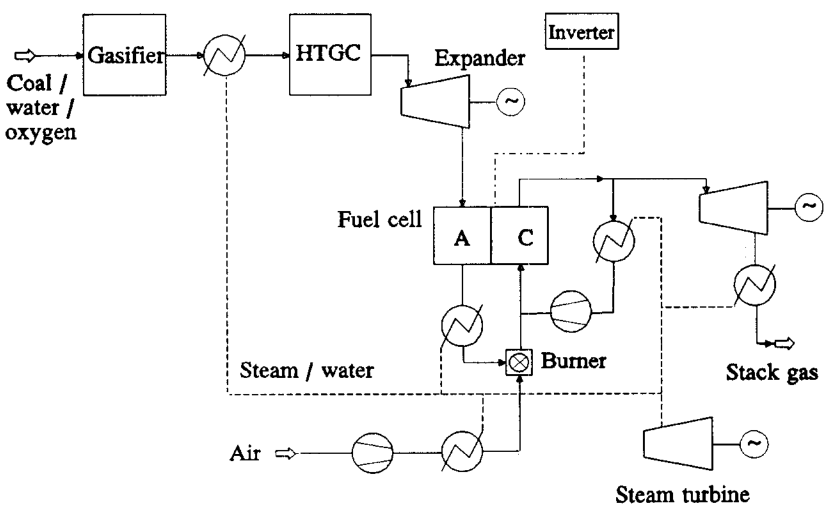

Fig. 2. Block diagram of an IGMCFC power plant with high-temperature gas clean-up equipment.

differences are that in the syngas cooler, the fuel gas is now cooled down to 600 °C after which it is cleaned in the HTGC and that high-temperature cathode recycle blowers are used. Again, expanders are used to lower the pressure of the fuel gas to the operating pressure of the MCFC stacks.

Table 5 summarizes the performance results of the two IGMCFC study cases. Also included, for comparison, are the performance results of a Texaco IGCC study case prepared by ECN.

TABLE 5

IGMCFC performance summary

	Texaco MCFC LTGC	Texaco MCFC HTGC	Texaco IGCC LTGC
Plant performance			
Coal feed rate (MW_{th} LHV)	1206	1206	1206
Net power production (MW_e)	593.7	641.1	503.3
System efficiency (% LHV)	49.2	53.2	41.7
Power production (MW_e)			
Producers			
Gas turbines			298.2
Fuel cells	378.4	373.6	
Fuel gas expanders	23.2	53.3	10.4
Cathode exhaust gas expanders	176.2	170.9	
Steam turbines	220.3	228.1	271.6
Total	798.1	825.9	571.2
Consumers (MW_e)			
MCFC blowers	33.1	25.8	
MCFC air compressors	91.6	83.5	
Oxygen plant	55.6	56.3	40.9
Others (pumps, etc.)	24.1	19.2	27.0
Total	204.4	184.8	67.9
Emissions			
Particulates (mg/kWh)	<6	<6	<6
SO_2 (mg/kWh)	26	23	66
NO_x (mg/kWh)	20	18	450
CO_2 (g/kWh)	673	623	794
MCFC performance			
Pressure (bar)	4	4	
Temperature (°C)	650	650	
Power produced (MW_e d.c.)	386.1	381.3	
Current density (A/m^2)	1500	1500	
Cell voltage (V)	0.73	0.72	
Fuel utilization (%)	85	85	
Oxygen utilization (%)	13	15	

Both IGMCFC power plants involve two Texaco gasifiers and two fuel cell trains. Each fuel cell train includes one set of auxiliary equipment (gas clean-up devices, fuel gas expanders) and 100 fuel cell vessels. Each vessel contains an insulated fuel cell stack assembly. The assembly includes four 500-kW fuel stacks and the equipment to route the gases to and from the stacks. The air separation unit for the gasifiers operates at low pressure to minimize power consumption.

The 500-MW_e IGCC power plant, used for comparison also involves two Texaco gasifiers, processing about 4000 t/day of coal, which are integrated with a power block incorporating two Siemens V94.2 gas turbines, one HRSG, one set of steam turbines and an elevated pressure air separation unit.

As can be seen from Table 5, IGMCFC plant performance will improve from 49.2% (LHV) to 53.2% (LHV) when HTGC is introduced. The power summary indicates that the output of the fuel gas expanders is increased in the IGMCFC system with HTGC, due to the higher inlet temperature and the higher pressure ratio. In both systems the fuel cell performance is almost the same, because the operating conditions are almost identical. Because more high-quality heat is available for high-pressure steam in the IGMCFC system with HTGC, the steam turbines produce more power.

The total power consumption in the IGMCFC system with HTGC is lower due to the system simplifications, resulting in lower pressure losses and lower power consumption of the HTGC. As indicated in Table 5, the power consumption of the recycle blowers is very sensitive to the pressure drops in the recycle loops and, therefore, special attention must be paid to the design of the fuel cell stacks and the heat exchange equipment. With both systems it is possible to achieve significantly higher system efficiencies than in state-of-the-art IGCC systems, resulting in lower CO_2 emissions. In addition, both SO_2 and NO_x emissions are lower, due to the low sulphur tolerance of the fuel cell and the operating temperature.

Another possible route to higher IGMCFC system efficiencies is the integration of the more advanced gasification processes, such as the Exxon process, with MCFC stacks. ERC studied several designs based on ERC internal MCFC stacks and the Exxon catalytic process. Both the heat and the hydrogen effluent of the fuel cell stacks are recycled back to the gasifier (see Fig. 3). The results of this study indicated that system efficiencies up to 53.5% HHV (55–56% LHV) can be achieved with the so-called thermochemical IGMCFC systems.

4.2. Coal-fuelled solid oxide fuel cell systems

In 1992, the Electric Power Research Institute (EPRI) performed an evaluation study on the Westinghouse SOFC technology for electricity utility applications in Japan [6]. The study showed net electrical efficiencies approaching 47% HHV (49% LHV) for a 300-MW_e integrated coal-gasification SOFC power plant. In this system two Shell oxygen-blown gasifiers were proposed for coal conversion. The SOFC system is composed of 96 modules generating 60% of the total electricity. Each module has a nominal d.c. power rating of 2.5 MW, and is composed of 9792 cells. In the heat recovery steam generation system high-quality steam is generated for electricity generation. The system also includes a high-temperature gas clean-up subsystem for particulate and sulphur removal (zinc titanate). The sulphur extracted from the coal gas is recovered

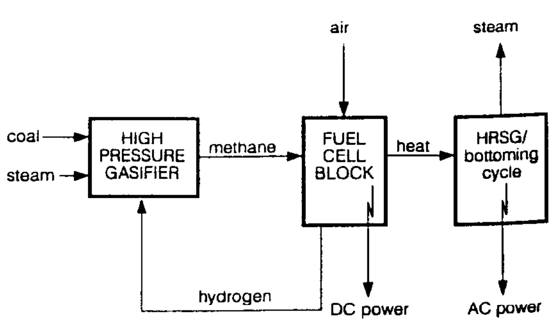

Fig. 3. Thermochemically integrated gasification molten carbonate fuel cell system (ERC).

in a sulphur recovery system which consists of a conventional tail gas treatment process, an Allied Chemical sulphur recovery unit. The total sulphur removal efficiency is about 99%. The SO_2 and NO_x emissions are comparable with the SO_2 and NO_x emissions of the IGMCFC systems discussed above (see Table 5).

Because of its higher operating temperature, the SOFC may be used in a triple cycle design, i.e., the combination of an SOFC, a gas turbine and a steam cycle in one system. A study by Dornier [7] indicated that with natural gas, an efficiency of 74% LHV may be possible for a triple cycle internal reforming SOFC system. A similar system, fuelled with coal-derived gas, should be able to achieve efficiencies of 55 to 60% LHV assuming a gasifier efficiency of 75 to 81% (see Table 1). Detailed assessment studies are, however, needed to give more confidence in these efficiencies.

5. Prospects

In a survey of the state-of-the-art and prospects of fuel cell systems performed by ECN and Tebodin [8], data were acquired on the future costs and performance of fuel cell subsystems via a literature survey, by interviewing experts and by a questionnaire sent to developers of fuel cells and systems. This survey made clear that the development of integrated coal-gasification fuel cell systems (IGMCFC or IGSOFC) is still far off. A significant market share for this type of clean coal technology for large-scale electricity generation is not envisaged before the year 2015.

5.1. Competing technologies and comparisons

In Section 4 integrated coal-gasification fuel cell systems are compared with more or less state-of-the-art IGCC systems. However, to assess the market potential of coal-fuelled fuel cell power plants the promise of new clean coal technology must be assessed alongside the performance and the development potential of current state-of-the-art systems. This means that by the year 2015 IGFC systems must be able to compete with, then, state-of-the-art clean coal technologies, such as advanced pulverized coal combustion and advanced IGCC systems.

An advanced pulverized coal combustion system would use an ultra-supercritical water/steam cycle and would represent the ultimate state of conventional power generation technology based on coal. The advanced pulverized coal combustion system is based on continued development towards higher efficiency, from 30% LHV in the early 1950s to 42–44% LHV for plants currently in operation. Further development of this technology depends mainly on the steam conditions. Critical in the future development are the materials to be used in the water/steam systems.

The design of pulverized coal combustion power plants using 325 bar/625 °C steam conditions might start before the end of this century. Environmental improvements, especially NO_x reduction, can be achieved by the application of selective catalytic reduction (SCR). This will however result in a small decrease in efficiency and additional costs.

The natural gas-fired combined cycle is the most efficient and economical technology available today for large-scale power generation. This technology benefits from the ongoing development in combustion turbines and the many years of development of large steam turbines for electricity generation. New gas turbine combined cycles can operate today on clean fuel, i.e., natural gas, with efficiencies of 50 to 52% (LHV). With the anticipated progress in gas-turbine technology using higher inlet temperatures and pressure ratios, efficiencies up to 60% (LHV) for natural gas-fired combined cycles are envisaged in the next 20 to 30 years.

The combined cycle technology has become so efficient that it can incorporate the fuel processing losses associated with coal gasification. Therefore, present integrated gasification combined cycle systems are able to achieve efficiencies of 43 to 44% (LHV).

IGCC power generation systems will also take advantage of progress in gas turbine technology and in high-temperature gas clean-up technologies. Future IGCC power plants should therefore be able to achieve efficiencies up to 50% LHV.

The SO_2 emissions of present IGCC power plants are already very low (see Table 5). A sulphur balance indicates that 98.9% of the sulphur of the coal can be removed with conventional cleaning technologies. The SO_2 emissions can be reduced further when the remaining SO_2 in the tail gas from the sulphur recovery unit is converted to H_2S in the Scott process, and routed back to the sulphur removal unit. This will result in an overall sulphur removal efficiency of 99.4% and in lower NO_x emissions due to absence of a tail gas incinerator.

Modern gas turbines can achieve NO_x emissions of less than 25 ppm on coal-derived gas. With the ongoing development of low-NO_x burners, future gas turbines with higher inlet temperatures should be able to achieve the same NO_x emission levels.

In Table 6, the efficiencies and emissions of future coal-fuelled power generation technologies are presented. These figures are based on the assumption that the developments mentioned above will be successful.

From Table 6 it is clear that future coal-fuelled fuel cell power plants will be able to achieve higher efficiencies than other competing power generation technologies, and that their environmental impact is likely to be lower. It also is clear that this environmental advantage is not as large as has often been stated, and that with additional clean-up technologies, the IGCC could achieve the same emissions levels as the IGFC systems.

However, the NO_x emissions of IGFC systems are lower than those of advanced IGCC systems. Post-combustion treatment such as SCR could be employed to reduce the NO_x emissions from the gas turbine exhaust gases in IGCC systems by almost nearly 80%. This will also result in a small decrease in efficiency, and additional costs. The very low SO_2 emissions for fuel cell power plants reflect the fact that fuel cells require an almost sulphur-free fuel gas. If the gas turbine in the advanced IGCC system is fired with fuel gas with the same low-sulphur content, the SO_2 emissions would be comparable with those of the IGFC system.

TABLE 6

Efficiencies and emissions of coal-fuelled power plants; projection for the years 2020–2030[a]

	PC–FGD/de-NO_x	IGCC	IGFC
Efficiency (% LHV)	46	50	55
SO_2 (mg/kWh)	160	30	2
NO_x(mg/kWh)	260	185	<10
CO_2 (g/kWh)	720	660	600
Dust (mg/kWh)	45	<6	<6

[a]The efficiencies and the emissions apply for full load operation. PC–FGD/de-NO_x = pulverized coal combustion with fuel gas desulphurization and de-NO_x; IGCC = integrated coal gasification combined cycle; IGFC = integrated coal gasification with molten carbonate or solid oxide fuel cell.

5.2. Carbon dioxide recovery in coal-fuelled cell systems

The growing awareness of the risk of a climate change due to greenhouse-gas emissions has triggered research and development of CO_2 recovery techniques all over the world. Therefore, the impact of CO_2 recovery on the efficiencies and CO_2 emissions of both advanced IGCC and IGMCFC system has also been assessed by ECN [9–12]. In these studies advanced CO_2 recovery techniques such as CO_2/O_2 combustion and the use of membrane separation have been examined because of the envisaged market introduction of advanced IGCC and coal-fuelled fuel cell power plants will not be before 2015. The main results of these assessments are summarized in Table 7.

Due to the specific properties of the MCFC and SOFC, active CO_2 recovery is simplified in IGMCFC or IGSOFC power plants, therefore efficiency penalty is less than for IGCC or pulverized coal power plants with CO_2 recovery. This is shown in Table 7. When CO_2 recovery in coal-fuelled power plants becomes necessary to meet national and international policy goals, a limited availability of storage capacity will be available, and the specific CO_2 emissions and CO_2 storage per kWh output are important variables which will determine preferences for different recovery options. In this case, the IGFC has an advantage over the other advanced power generation systems.

5.3. Market and economy

The future market for fuel cell systems will mainly be dictated by the demands for low price, high efficiency and low emissions. Fuel cells, however, will have to face severe competition from competing and still developing technologies such as efficient gas turbines in combined cycles. Fuel cell systems will also have to compete with alternative energy generation techniques such as solar and wind energy. However, the role fuel cells will play in the future will be set by their economical efficiency and emissions regulations. The most important applications are therefore expected where avoiding pollution is overriding, as in densely populated areas. Market penetration will depend on the price on the total system, compared with prices for competing technologies equipped with emission control equipment.

The key uncertainties which could limit the adoption of fuel cell technology for central power generation are fuel cell lifetime and the cost of the fuel cell system.

TABLE 7

Efficiencies and CO_2 emissions of coal-fuelled power plants with CO_2 recovery; projection for the years 2020–2030

	PC CO_2/O_2 combustion	IGCC CO_2/O_2 combustion	IGCC shift and absorption	IGMCFC membrane separation
Net efficiency (% LHV)	37	45	42	50
CO_2 recovery rate (%)	96	96	88	97
Specific CO_2 emission (g/kWh)	36	30	94	20
Specific CO_2 storage (g/kWh)	860	710	690	640

At this moment, no experience is available with fuel cells operating on coal-derived gas. However, two test facilities are under construction, one in the USA (DOW, Plaquemine, LA) for a 20-kW ERC MCFC stack, with another in The Netherlands (SEP, Buggenum) for a 250-kW MCFC. In the near future, these test facilities will provide data on the performance and lifetime of MCFC stacks fuelled with coal-derived gas.

The comparison of the electricity generation costs is based on reference data summarized in Table 8.

Investment costs (including allowance for funds during construction) and annual operating and maintenance costs are shown in Table 9. The investment costs for advanced pulverized coal combustion systems, including FGD and de-NO_x will be 2000–2200 Dfl/kW_e by the year 2000. No further reduction is foreseen. By the year 2010 the investment costs of an advanced IGCC system will reach a level of about 2800–3000 Dfl/kW_e or 2910–3110 Dfl/kW_e for advanced IGCC systems with SCR. Investment costs for IGFC systems are estimated to be 3500 Dfl/kW_e by the year 2015 and 3150 Dfl/kW_e by the year 2030.

The electricity generation costs at load factor of 85% are 7.05–7.24 cents/kWh_e for the PC–FGD/de-NO_x plant, 7.75–7.94 cents/kWh_e for the advanced IGCC plant and 8.42–8.82 cents/kWh_e for the IGFC plant. If the IGCC power plant is equipped with an additional SCR to bring the NO_x emissions at the same level as the NO_x emissions of the IGFC power plant, the electricity generation costs will increase by 0.37 cents/kWh_e.

With a coal price of 5 Dfl/GJ and the anticipated investment costs and fuel cell lifetime, IGFC systems have higher electricity generation costs. The competitiveness

TABLE 8

Economic reference data

Reference year, price level	1992
Plant book life (except fuel cells)	25 years
Book life fuel cell stacks	10 years
Method of depreciation	annuity
Real rate of interest	5% per annum
Plant load factor	85%
Coal price	5 Dfl/GJ

TABLE 9

Investment and operating costs[a]

	PC–FGD/de-NO_x	IGCC	IGFC
Specifice investment costs (Dfl/kW_e)	2000–2200	2800–3000	3150–3500
Fixed O&M costs (Dfl/kW_e per annum)	60	70	70
Variable O&M costs (Dfl/GJ_e)	1.2	1.48	1.7

[a]Currency exchange rate 1.85 Dfl./US$.

of IGFC systems will improve at lower investment costs and with an extended fuel cell stack lifetime. Higher coal prices will also improve their economical competitiveness.

6. Conclusions

1. Fuel cells can use coal as primary fuel via coal gasification.

2. High-temperature fuel cells (MCFC and SOFC) offer the best opportunities for coal-fuelled fuel cell power plants because they are able to convert both H_2 and CO and reject their heat at temperatures high enough for raising high quality steam for electricity generation in a bottoming cycle.

3. Due to their very low tolerance level for impurities, adequate clean-up technologies for the coal-derived gases are essential for the viability of coal-fuelled fuel cell power plants.

4. Coal-fuelled fuel cell power plants using gasification processes developed for IGCC applications offer advances in efficiency and environmental impact over current state-of-the-art IGCC and pulverized coal power plants.

5. Gasification processes appropriate for IGCC power plants might not be optimal for coal-fuelled fuel cell power plants. The thermochemical integration of fuel cells with low-temperature, catalytic gasification processes is a possible route to higher efficiencies. The environmental impact of these systems, however, need to be assessed very thoroughly.

6. The introduction of coal-fuelled fuel cell power plants is not envisaged before 2015.

7. With the anticipated progress in gas-turbine and gas clean-up technologies, coal-fuelled fuel cell power plants will face severe competition from advanced IGCC power plants, despite their expected higher efficiencies.

8. Further R&D, supported by assessment studies, is necessary to expand the lifetime of fuel cells and to reduce the costs and complexity of large fuel cell systems.

9. Coal-fuelled fuel cell systems facilitate CO_2 recovery and separation and therefore their efficiency penalty is expected to be less than that for other coal-fuelled power generation systems.

References

1 P.C. van der Laag and D. Jansen, The status of the Dutch fuel cell activities and the route to commercialization, *Proc. Int. Fuel Cell Conf., Makuhari, Japan, Feb. 3–6, 1992,* pp. 25–28.

2 H. Scott David, Advanced power generation from fuel cells – implications for coal, *IEACR-59,* London, UK, IEA Coal Research, July 1993.

3 A.B.J. Oudhuis, D. Jansen and P.C. van der Laag, Concept for a coal fuel cell power plant with CO_2 removal, *Modern Power Systems,* Nov. 1991, pp. 25–29.

4 D. Jansen, A.B.J. Oudhuis and J.S. Ribberink, Different options for integrated coal gasification fuel cell power generation plants and their potential to reduce CO_2 emissions, *EPRI: 11th Conf. Coal Gasification Power Plants, Oct. 21–23 1992, San Francisco, CA, USA.*

5 P.T. Alderliesten and D. Jansen, System study high temperature gas cleaning at IGCC systems, *Joint system study performed by ECN, KEMA, Stork Boilers and TNO,* Nov. 1990. (Executive summary in English is available at Novem, Netherlands agency for energy and environment.)

6 Evaluation of the Westinghouse solid oxide fuel cell technology for electric utility applications in Japan, prepared by Westinghouse Electric Corporation, *EPRI TR-10073, Project 1676-13, Final Rep.,* May 1992.

7 W. Dönitz, E. Erdle, W. Schaffer, R. Schamm and R. Spah, Status of SOFC development at Dornier, *2nd Int. Symp. Solid Oxide Fuel Cells, July 2–5, 1991, Athens, Greece,* Commission European Communities, Luxembourg, pp. 75–84.
8 D. Jansen, Fuel cells, Present state-of-the-art and prospects, Netherlands Energy Research Foundation, Petten, The Netherlands, *ECN-CX-93-043,* May 1993 (in Dutch).
9 A.B.J. Oudhuis, Inventory of techniques for CO_2 removal from fuel gas or reformer gas, *ECN-C-92-043,* Netherlands Energy Research Foundation, Petten, The Netherlands, July 1991.
10 J.S. Ribberink, D. Jansen and A.B.J. Oudhuis, Technical and cost evaluation study on power and CO_2 production in an integrated gasification combined cycle, *ECN-CX-92-060,* Netherlands Energy Research Foundation, Petten, The Netherlands, June 1992.
11 J.S. Ribberink, R. van Ree, A.B.J. Oudhuis and D. Jansen, Studies on integrated gasification combined cycle with CO_2 removal, *ECN-CX-93-063,* Netherlands Energy Research Foundation, Petten, The Netherlands, July 1993.
12 P. Lako, Compilation of CO_2 recovery technologies for natural gas and coal-fuelled power plants, *ECN-C-92-064,* Netherlands Energy Research Foundation, Petten, The Netherlands, Oct. 1992 (in Dutch).