

Electrochemical Engineering and Energy

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PREFACE

This volume contains the papers presented at the Third European Symposium on electrochemical engineering "Electrochemical Engineering and Energy", held on March 23-25, 1994 in Nancy, France. This meeting was organised by the Laboratoire des Sciences du Génie Chimique, CNRS, and the Centre de Perfectionnement des Industries Chimiques, in conjunction with the Groupe Français de Génie des Procédés, the Society of Chemical Industry, Dechema, and the European Federation of Chemical Engineering.

The organisers would like to thank the members of the Scientific Committee for the careful selection and refereeing of the papers. We are grateful to all contributors for the thorough preparation of their manuscripts. Thanks are due to the International Society of Electrochemistry, District Urbain de Nancy, Région Lorraine, Electricité de France, Institut National Polytechnique de Lorraine, and CNRS for their support.

The meeting was devoted to the role of electrochemical engineering and its relationship to the general issue of energy. The twenty-four papers contained here represent new research results and the potential technological developments in a variety of important and relevant areas of the field. The remaining three papers are expert reviews in areas of current technological concern where electrochemical engineering can clearly be seen to have major relevance to energy policy and environmental protection.

The papers cover a wide range of material from energy conversion, through electrochemical transport processes, electrochemical synthesis and modelling of electrochemical cells and processes. Throughout the book the reader will be aware of the multidisciplinary interaction of electrochemistry with other areas such as materials science, fluid mechanics, mass transfer and systems analysis. It is hoped that the papers present a convincing scientific base but are also relevant to future progress development and innovation in the field.

The final paper, a review paper on "Towards a Cleaner Environment using Electrochemical Techniques" by Klaus Jüttner and Gerhard Kreysa, was given in response to the award by the SCI of its Castner Medal to Professor Kreysa in recognition of its outstanding and distinguished work in electrochemical engineering.

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ON THE ENVIRONMENTAL IMPACT OF ENERGY CONVERSION SYSTEMS

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ABSTRACT

An analysis of the energy consumption and the associated emissions for power plants and road traffic is presented for West Germany as a typical highly industrialized country. While the former is the sector of highest energy consumption and CO₂ emission, the latter shows the highest emissions with respect to NO_x, CO and volatile organic compounds (VOC). Both sectors, each being prominent in its own way, are analyzed with respect to the underlying technical principles of the present technology in comparison to a potential future use of fuel cell systems. The energy consumption and emission levels of fuel cells in stationary electricity production in power plants and in vehicle application in road traffic is compared with the corresponding conventional systems. Conclusions for the future technological development can be drawn from the results of the presented analysis.

INTRODUCTION

In the past 20 years the global energy market has been subjected to intensive changes. Limited primary energy supply and the environmental impact associated with energy conversion lead to new legal requirements at both the national and the international level. New energy conversion processes are being developed in order to reduce the specific primary energy consumption and the associated specific emissions.

An analysis of primary energy requirements in the various areas in an industrialized country like West Germany (1990) reveals that power and heating plants as well as households and small businesses are the top primary energy consumers whereas traffic plays only a minor role. Conversion losses related to primary energy demand in power and heating plants amount to 23 %; the fraction of end energy consumption in road traffic amounts to 16 % (total traffic: 18 %). Almost 40 % of the total national primary energy input is used for conversion processes in power and heating plants.

The CO₂ emission balance specifies approximately 35 % emissions from power and heating plants, whereas road traffic with about 18 % (Figure 1) ranks behind industrial firing systems (20 %).

For CO, NO_x, and VOC (volatile organic compounds) emissions, which contribute to the formation of photochemical secondary pollutants in the troposphere near ground level,

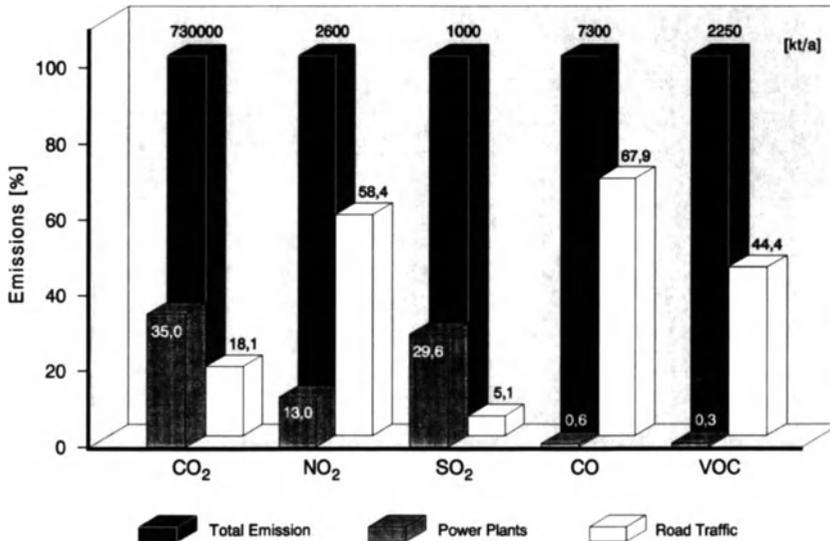


Figure 1. Percentage of Emissions: West Germany 1990³

the picture is quite different. Emissions from road traffic are at the top with more than 44 %. Power and heating plants contribute 13 % to NO_x emissions, < 1 % to CO emissions, 30 % to SO₂ emissions and < 1 % to organic compounds (VOC) (Figure 1).

These data show the significance of power and heating plants with respect to the consumption of primary energy and the emissions of carbon dioxide and sulphur dioxide on the one hand and the importance of road traffic with respect to legally restricted emissions of CO, NO_x and VOC on the other hand; such results are typical of many industrial countries. Consequently, a number of national and also international efforts are undertaken aiming at developing solutions for new energy conversion processes in the sector of power and heating plants and in the field of vehicle drive systems, especially for road traffic.

This paper describes the state of the art and the development potential for conventional and new thermal power processes as well as energy conversion processes based on fuel cells for electricity and heat production using fossil fuels. The discussion centres on the future use of high-temperature fuel cells and the resulting potential for lower energy consumption and reduced emissions in comparison to conventional thermal power processes. In addition, conventional drive systems based on internal combustion engines are compared with electric vehicles either with batteries or with fuel cells in terms of their energy consumption and emissions.

CONVERSION SYSTEMS FOR STATIONARY ELECTRICITY PRODUCTION

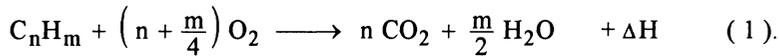
Primary Energy and Emissions: Worldwide - Germany

The consumption of fossil fuels was negligible until the middle of the 18th century. Energy requirements for urban and rural space heating, for crafts and small industries were covered by regenerative sources of primary energy; man-made CO₂ emissions from fossil fuels were not important. This situation changed significantly with industrialization. The beginning of the industrial era was marked by the invention of the steam engine, the first machine which allowed man to convert the chemical energy contained in fuels into

mechanical energy. It was originally applied in mining and thus fired with coal. The mechanization of other industries and manufacturing methods as well as the use of steam engines in railways promoted this form of energy conversion. The second industrial revolution introduced electricity on a broad scale; this was initially generated exclusively on the basis of coal. As motorized traffic developed, another CO₂ source was added, the fossil fuel being oil which, together with natural gas, gradually began to replace coal. The current situation of industrialized countries is as follows:

- The prosperity of an industrial country is closely related to its degree of industrialization and its energy consumption. Apart from the OPEC states and Eastern Europe, today a country's prosperity is deduced from the per-capita energy consumption of its citizens.
- In spite of the introduction of nuclear and other energies, most of our energy requirements are still provided by fossil fuels.

Conventional methods of using the energy contained in fossil fuels is thermal combustion which generates heat from hydrocarbons according to the reaction



This leads currently to a carbon consumption from fossil fuels and an associated carbon dioxide emission of 5.4×10^9 t/a C and 19.8×10^9 t/a CO₂, respectively, the error of the estimate being $\pm 9\%$ ¹. This CO₂ input into the atmosphere has led to an initially slow, but then accelerated increase of the CO₂ concentration in the earth's atmosphere (see Figure 2)². It is being recognized today that this, in conjunction with other gases, can cause the greenhouse effect, i.e. a rise in global temperatures.

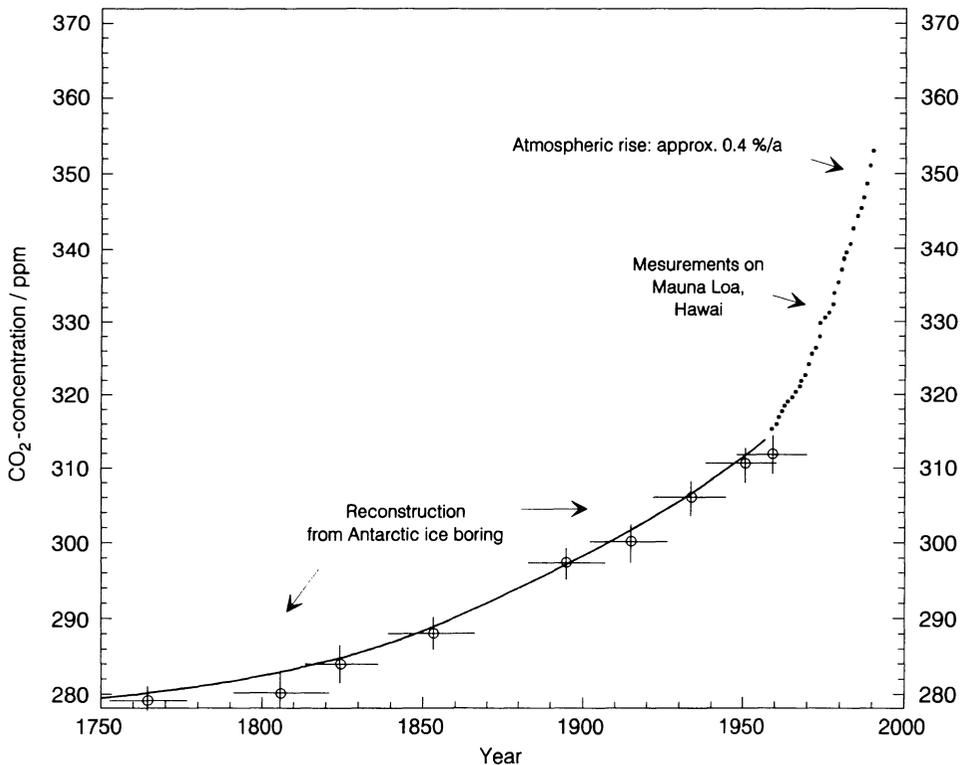


Figure 2. Rise of the CO₂ Concentration in the Earth's Atmosphere ²

in air. These emissions are NO and NO₂, both referred to as NO_x, as well as SO₂, carbons and particles. A detailed list of emissions in West Germany is shown in

Table 1. Various air pollutants according to their sources (West Germany, 1990)³

		CO ₂	CO	NO _x as NO ₂	SO ₂	VOC	Parti- cles
Total quantity in million t/a		730	7.3	2.60	1.00	2.25	0.45
Power and heating plants	%	35.0	0.6	13.0	29.6	0.3	5.1
Industrial firing	%	19.8	10.0	9.1	31.3	0.4	4.0
Industrial processes	%	3.0	8.3	0.6	8.5	4.5	27.7
Small businesses	%	6.5	1.5	1.4	5.1	0.2	1.3
Households	%	12.9	7.9	2.8	8.3	1.2	5.3
Road traffic	%	18.1	67.9	58.4	5.1	44.4	13.3
Other traffic	%	4.7	3.7	14.7	12.0	3.4	4.6
Use of solvents	%	-	-	-	-	45.5	-
Transport of bulk goods	%	-	-	-	-	-	38.7

le 1³. It can be seen that electricity generation and traffic contribute significantly to the mentioned emissions. In the following the emissions produced in the energy consumption sector of power and heating plants will be discussed in more detail.

The most important gaseous impurities in flue gas from electricity generation plants are CO₂, NO_x, SO₂ and particles. In order to prevent SO₂ emission the sulphur can be removed from the fuel or the flue gas is desulphurized. For energy conversion processes requiring almost sulphur-free fuel gas for technical reasons such processes treating fuel can not be introduced due to high costs. This applies, in particular, if regulatory limits for sulphur emissions permit cheaper desulphurization techniques in the offgas flow.

Particles are of significance only as fly ash in coal-fired power plants; effective filtration systems are available. It should be generally noted that the removal of NO_x, SO₂ and particles from offgases leads to efficiency losses for energy conversion in power plants.

Here, the discussion should be limited to CO₂ and NO_x which are the basic emissions in the thermal combustion of fossil fuels. CO₂ contributes about 50 % to the greenhouse effect and NO_x plays a role in surface water and soil acidification and in the formation of tropospheric ozone.

Energy Conversion Systems

According to Figure 3⁴ there are two principle routes for converting the energy contained in fossil fuels into electricity. The first route comprises the thermal conversion processes in heat engines, which are classified into those with external and those with internal combustion. In a conventional steam power plant, the fuel is burned and steam is produced at high pressure and temperature. In gas turbine power plants, the combustion chamber is part of the turbine and combustion takes place inside the heat engine. Turbines and electrodynamic generators convert the enthalpy contained in the steam or gas into mechanical energy and subsequently into electricity. The second conversion route is the fuel

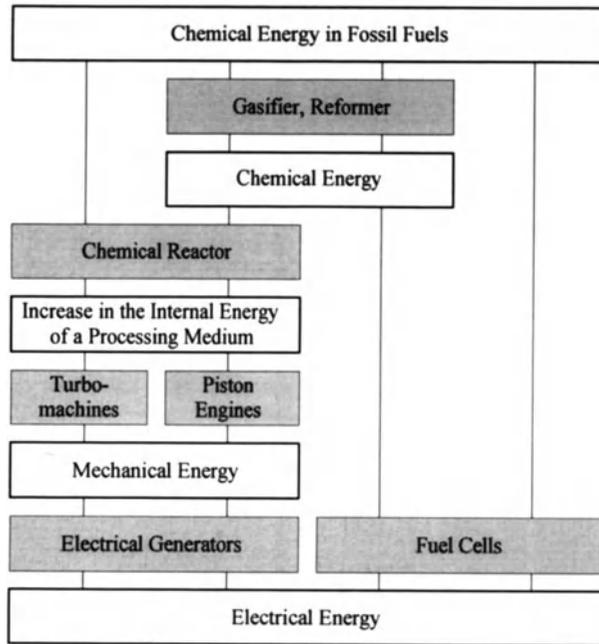


Figure 3. Conversion Routes of Fossil Fuels ⁴

cell process. In a fuel cell, chemical energy is directly converted into electrical energy by means of an electrochemical reaction. The fuel is continuously fed to the cell and reaction products are continuously removed.

The maximum theoretical efficiency of a thermal process is given by the Carnot Cycle:

$$\eta_C = 1 - \frac{T_l}{T_u} \quad (2).$$

T_l and T_u are the lower and upper temperatures during isothermal expansion or compression steps of this cycle.

This is in contrast to the theoretical efficiency of an electrochemical process given by

$$\eta_{th} = \frac{\Delta G}{\Delta H} = \frac{\Delta H - T \cdot \Delta S}{\Delta H} = 1 - \frac{T \cdot \Delta S}{\Delta H} \quad (3).$$

The fuel cell converts directly the fraction ΔG into electricity. ΔH is the chemical energy stored in the fuel. The entropic energy loss, $T \cdot \Delta S$, is relatively small in most cases. The theoretical efficiency, η_{th} , for fuel cell processes with oxygen as the oxidant is $> 90\%$ under standard conditions at 25°C , if the lower heating value (LHV) of the fuel is used for ΔH . A comparison between thermal conversion process and fuel cell operation in practically applied processes is shown in Table 2. It should be noted that the η_{th} -values are based on

Table 2. Comparison of Heat engines and Fuel Cells in Power Plants

System	Operation Temperature or Range in $^\circ\text{C}$	Carnot Efficiency η_C	Theoretical Efficiency η_{th} based on $\text{H}_2 + \text{O}_2$ ¹⁾	Technically achieved η_{el} based on Natural Gas + Air (Cell Efficiency based on synthesis gas) ¹⁾
Gas engine				0.30 - 0.36
Gas turbine	1100 - 500	0.44		0.32 - 0.36
Steam power plant	535 - 40	0.613		0.42 - 0.45
Combined-cycle power plant (CCP)	1100 - 30	0.78		0.53 ²⁾
PAFC packaged cogeneration plant	200		0.87	0.40 ^{3),4)} (0.55) ⁴⁾
SOFC cogeneration plant	1000		0.71	0.40 - 0.60 ⁵⁾ (0.60 - 0.65)
Triple process SOFC + CCP				0.63 - 0.68 ⁶⁾ (0.60 - 0.65)
¹⁾ relative to lower heat value ²⁾ KWU/Ambarli (Turkey) ³⁾ ONSI, with reformer		⁴⁾ given by Wendt et al. ¹¹ ⁵⁾ expected by Riensche et al. ⁹ ⁶⁾ expected by Reinecke et al. ¹²		

pure hydrogen and pure oxygen. The technically achieved η_{el} -values are efficiencies of complete systems for which methane was taken as the energy carrier.

Fuel cell types are distinguished according to their electrolytes and vary with respect to their operating temperatures:

- Alkaline Fuel Cell (AFC) approx. 80°C
- Phosphoric Acid Fuel Cell (PAFC) approx. 200°C
- Molten Carbonate Fuel Cell (MCFC) approx. 650°C
- Solid Oxide Fuel Cell (SOFC) approx. 1000°C

The AFC is mentioned because it is fairly far advanced in its development. It may not be suitable for broader application because it can only be operated with high-purity hydrogen and oxygen. The types of fuel cells under development for stationary electricity generation are the PAFC as a low-temperature fuel cell and MCFC and SOFC as high-temperature fuel cells. Typical materials used in these cells are shown in Table 3.

The fuel used is synthesis gas prepared by reforming natural gas or by coal gasification. The oxidant is air. In practice the fuel is not completely converted; residual gas leaves the cell together with the product gas from electrochemical oxidation, but it can be used for

heat production in residual combustion. In Table 2 the cell efficiency based on synthesis gas from methane is shown along with the overall efficiencies η_{el} of fuel cell power plants.

The heat produced due to irreversibilities of the electrochemical process and the heat from residual gas combustion can be used thermally. Heat is, for example, required for reforming natural gas.

Table 3. Examples of Electrode and Electrolyte Materials

	Anode	Electrolyte [mobile ions]	Cathode
PAFC	carbon + Pt	H ₃ PO ₄ [H ⁺]	carbon + Pt
MCFC	carbon + Pt	Li ₂ CO ₃ -K ₂ CO ₃ in LiAlO ₂ -matrix [CO ₃ ²⁻]	NiO Li-doped
SOFC	electronic conductor Ni-ZrO ₂ -Cermet 30 Vol% NiO 70 Vol%(ZrO ₂) _{0.9} (Y ₂ O ₃) _{0.1}	ionic conductor (ZrO ₂) _{0.92} (Y ₂ O ₃) _{0.08} [O ²⁻]	electronic conductor (perovskite) La _{0.8} Sr _{0.2} MnO ₃

The current status of the technical development of fuel cells depends on the type of system. Up to 11 MW are reached for the phosphoric acid fuel cell, which is the most advanced type on a technical scale. ONSI Corporation, USA, produces e.g. the PC25 type as a PAFC packaged cogeneration plant with an electrical output of 200 kW in a small-series production⁵. Complete commercialization together with competitive prices are expected by ONSI within the next few years. Material problems encountered for the MCFC due to corrosiveness of the molten carbonate and for the SOFC due to high temperatures still require intensive development work in materials research.

Thermal Conversion Systems

In the following, the terms "system efficiency" and "cell efficiency" will be distinguished. Both denote the ratio of electrical power output, P_{el} , to chemical energy, \dot{H} , supplied with the fuel:

$$\eta_{el} = \frac{P_{el}}{\dot{H}} = \frac{P_{el}}{\dot{m}_f \cdot \Delta H} \quad (4)$$

They differ with respect to the boundaries for which energy changes are taken into account:

- the system efficiency compares the electricity output with the fuel supply for the entire plant
- the cell efficiency compares the electric current at the cell terminals with the fuel input at the gas inlet of the cell stack.

The chemical energy input, \dot{H} , is calculated from the mass flow \dot{m}_f and the lower heating value (LHV) of the fuel.

Large Power Plants. The technologies currently used for thermal energy conversion in power plants are the steam- and the gas-turbine process or a combination of both. Their system efficiencies are mainly determined by gas or steam pressure and temperature.

Irreversibilities, friction and other losses cause practical efficiencies, which are substantially lower than the Carnot efficiency. Improvements have been done by increasing pressure and temperature at the turbine inlet, but limits are given by potential material problems. Other measures for an efficiency increase are improvements in heat supply and removal (e.g. multiple reheating, regenerative combustion air and feed water preheating, fluidized-bed combustion, wet cooling etc.).

Distinct thermodynamic improvements and thus a considerable increase in system efficiency are obtained by installing a gas turbine before the steam process. This so-called combined cycle is easy to realize for gaseous fuels and leads to low investment costs. State-of-the-art gas turbines derived from aeroplane engines are available with high power rating and high efficiency. Currently operated combined-cycle power plants with maximum efficiency can achieve a system efficiency of 53 % (KWU/Ambarli, Turkey, see Table 2).

If coal is used in combined cycle power plants, it must first be converted into a suitable gas. The two basic techniques are (i) combustion of the coal under pressure and expansion of the firing gases in the gas turbine and (ii) gasification of the coal into a combustible gas which, similarly to natural gas, is fed into the combustion chamber of the gas turbine. Problems are encountered in the first process with hot gas cleaning, since particles and other impurities from coal flue gases are detrimental to the gas turbine. In the gasification process, the synthesis product gas is cooled to temperatures permitting highly efficient and proven cleaning techniques to be used. The pollutants are extracted to such an extent that they do not represent any problem for the gas turbine. This, however, reduces the system efficiency and causes high investment costs. In this respect, coal gasification is at a disadvantage unless stricter requirements of emission reduction, i.e. SO₂ content in the offgas from coal-fired power plants, are being imposed.

The nitrogen oxides NO and NO₂, summarized as NO_x, arise during fossil fuel combustion in the flame and the surrounding high-temperature zones. Reduction measures distinguish between those concerning combustion technology and those involving separation techniques. Combustion technologies such as premix burners, flue gas recycling, staged combustion or fluidized bed combustion aim at preventing NO_x by keeping peak temperatures as low as possible and/or having combustion partially taking place in a reducing atmosphere. For the separation of nitrogen oxides the flue gas is passed through a reactor. A solid catalyst is used to reduce NO_x to nitrogen and water by ammonia injection.

Table 4. Emissions from Different Types of Fossil-Fuel-Fired 600-MW Power Plants⁶

Power plant	η_{el} %	CO ₂ $\frac{g}{kWh}$	NO _x $\frac{mg}{kWh}$	SO ₂ $\frac{mg}{kWh}$	CO $\frac{mg}{kWh}$	VOC $\frac{mg}{kWh}$
Pulverized coal fired steam power plant	42	830	600	600	75	< 5
Combined cycle power plant with integrated coal gasification	45	770	305	155	65	< 5
Natural gas fired steam power plant	45	440	200	< 1	18	< 5
Natural gas fired combined cycle power plant	53	375	125	< 1	33	18

System efficiencies, emissions and their reduction in different conventional power plant types can be seen from Table 4⁶. Although the CO₂ emission is linked to the conversion efficiency, Table 4 clearly demonstrate the advantage of natural gas over coal because of the low specific carbon content of natural gas.

Cogeneration Plants. Cogeneration plants are energy conversion systems which provide useful heat in addition to electricity. If heat removal takes place at low temperatures, the Carnot efficiency is high (see equation 2), but this heat can not be used otherwise. A rise in temperature at the cold end lowers the yield of electrical power in steam power plants, but the extracted heat can be efficiently used e.g. as process steam. This operating procedure is referred to as cogeneration. Depending on customer requirements, the overall efficiency of cogeneration can be greater than in case of pure electricity generation.

In principle, cogeneration can be used for any type of power plant, but the influence of the equation 2 on steam turbines is great; they are very sensitive to an increase in cooling temperature. Water-cooled combustion engines supply waste heat at elevated temperatures without efficiency losses. Using the waste heat both of cooling water and of offgas up to 150°C cogeneration plants with combustion engines are only suitable for the heating of buildings and low-grade processes⁷. In this case packaged cogeneration plants with gas combustion engines located close to the heat consumers are a preferred application.

A cogeneration plant consists of one or several modules, equipped with the necessary heat exchangers for the use of cooling-water and offgas heat. Electricity and heat are simultaneously produced in plant operation. An additional boiler system is used when more heat is required than supplied by the cogeneration process.

For emission reduction in combustion engines, three techniques can be distinguished: lean-mix combustion, exhaust gas treatment in a three-way catalyst with a stoichiometric air/fuel ratio ($\lambda = 1$) and exhaust gas treatment with ammonia injection and post-oxidation in an oxidation catalyst. These measures involve costs, but the effectiveness is only sufficient in terms of the emission limits: the pollutant concentration in the released offgas is still in the order of 100 mg/m³ (see Figure 7).

Conversion Systems with High-Temperature Fuel Cells

Equation 3 gives the theoretical efficiency of energy conversion in fuel cells being very high at low temperatures. This suggests that the phosphoric acid fuel cell operating at temperatures of approx. 200°C seems best suited for stationary systems. Fossil fuels must, however, first be converted into a hydrogen-rich synthesis gas by reforming or gasification. The required heat cannot be covered by the waste heat of this cell type, because reforming takes place at approx. 850°C. In addition, the CO content in the synthesis gas must be reduced in a second process step. Due to these characteristics the system efficiency of a cogeneration plant with phosphoric acid fuel cell using methane only reaches approx. 40 % (see Table 2).

The situation is different for high-temperature fuel cells. Their high operating temperature increases the fraction of entropic energy loss $T \cdot \Delta S$ in electrochemical conversion. For hydrogen as fuel the theoretical efficiency is $\eta_{th} = 71.1 \%$ at standard pressure and 1000°C compared to 94.5 % at 25°C. If the fuel of the high-temperature system is methane, the amount and temperature of the heat loss from the electrochemical reaction is sufficient to supply the heat for reforming. An efficiency of $\eta_{th} = 87.7 \%$ is then calculated at 1000°C⁸.

The great advantages of high-temperature fuel cells of the MCFC and SOFC type using methane as the fuel are:

- The theoretical efficiency, η_{th} , of the overall system of a "natural gas fed fuel cell" is high in spite of high operating temperatures.
- The irreversible heat losses in electrochemical conversion supply enough heat required for natural gas reforming.
- The steam produced during the reaction in the fuel cell is also available at a high temperature level.
- CO can be oxidized electrochemically.
- Reforming can take place partially or entirely in the cell (internal reforming).

In the case of internal heat utilization, the reformer is integrated in the cell or stack. This permits particularly high system efficiencies to be achieved with natural gas as fuel. Various possibilities of optimizing a SOFC cogeneration plant have been presented⁹. The maximum calculated cell efficiency is given as 65 % for 100 % internal reforming and optimistic cell parameters. For an overall plant with SOFC as sole energy converter an electrical efficiency of about 55 % can be derived. In the case of external reforming, the heat and steam must be extracted or removed from the cell and fed to a separate apparatus, the reformer. This causes lower efficiencies.

Of particular importance are the low NO_x emissions from fuel cells. This is due to the low working temperatures in comparison to thermal combustion. Even the SOFC is still below the 1300°C limit above which pronounced formation of thermal NO_x sets in.

The SOFC operating principle is very simple due to the solid ceramic electrolyte involved, but material problems result from the high operating temperature. Three different cell designs have been basically tested to date: the "tubular concept", the "honeycomb concept" and the "planar cell concept". The tubular concept has been advanced by Westinghouse¹⁰. The planar cell concept involves a cell composed of plate-type elements (anode, electrolyte, cathode as a unit or separated, gas distribution and current conductor plates). Several cells form a stack. This design offers the advantage that its components are well suited for mass production, but problems of sealing the gas-containing spaces still exist. Up to now stacks of the kW class have been successfully tested.

In addition to corrosion problems resulting from the high chemical aggressiveness of molten carbonate, the MCFC process has the disadvantage, that carbon dioxide must always be present in the air at the cathode due to the electrode reactions. This requirement necessitates the separation of this component from the anode gas flow and its admixture to the cathode gas, a process step which makes the periphery more expensive¹¹. External and internal reforming processes are currently discussed for gas processing in MCFC.

In principle, systems with high-temperature fuel cells can be used both in large power plants and in decentralized electricity and heat production. A combination of fuel cells and thermal power plants can be an optimum solution in power plant design. The high temperature fuel cell is here installed as a so-called topping cycle before a thermal power process and contributes significantly to electricity production. However, high-temperature fuel cells are also very suitable as the sole energy converters in cogeneration plants.

Power Plants. As described above SOFC systems can be combined with thermal cycles to utilize the heat and the unused part of the fuel leaving the stack in a thermal process. A combination with a gas and steam cycle allows for maximum system efficiency but is most useful only in the > 10 MW class. Figure 4 shows a fuel cell, here an SOFC, as a topping cycle integrated into a combined cycle power plant. The essential process steps are briefly as follows:

Natural gas is reformed and the hydrogen-rich synthesis gas is cleaned and fed into the fuel cell. The electrochemical process produces electricity; the by-products heat and steam are partially recycled into the reformer unit. Since the fuel is not completely converted in the SOFC, the offgas undergoes combustion and enters a gas turbine. A conventional steam process is arranged after the turbine. The electrical energy produced by the SOFC system and by the generator coupled to the gas and steam turbines is fed into the grid.

Instead of natural gas it is also possible to use coal as the primary energy source, which must then be subjected to a gasification process. High demands are made on the purity of the product gas from coal gasification: substances like sulphur, chlorine and fluorine compounds acting as catalyst poisons must be separated from the fuel gas. The exact