Micro Gas Turbine and Fuel Cell –
A Hybrid Energy Conversion System with High Potential

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ABSTRACT

This paper reports an assessment of coupling micro gas turbine and high temperature fuel cell (SOFC) as a possibility to realize power plant with an efficiency of 75%. The application of such a technology will be in the decentralized feed-in of housing estates and buildings with electricity, heat and cooling energy. Nowadays the first implemented prototypes reach efficiencies among 57- 58% /1/. The paper shows the necessity of further developments to be able to reach an efficiency of 75%. The developments include improvements in all components of the system like compressor, turbine, bearing and the increasing of the operating temperature.

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1. INTRODUCTION

1.1 Energy conversion techniques

There are a great number of technologies and system, which can convert the different types of primary energy into electrical energy and heat. As a rule the conversion occurs in chains of several steps until the demanded energy form is available.

In Fig. 1.1, the energy supply conversion chains that are of interest regarding the production of electricity and heat, are schematically presented. Firstly two of these energy conversion processes are prescinded because they are not able to generate heat. These are wind turbines, which convert kinetic energy into mechanical energy, and photocells (photovoltaics), that convert radiation energy into electric energy. Furthermore, the energy conversion processes with photocells and fuel cells are distinguished from the remaining processes, due to the missing rotating components, i.e. the energy is not converted into mechanical energy in any of the conversion steps.

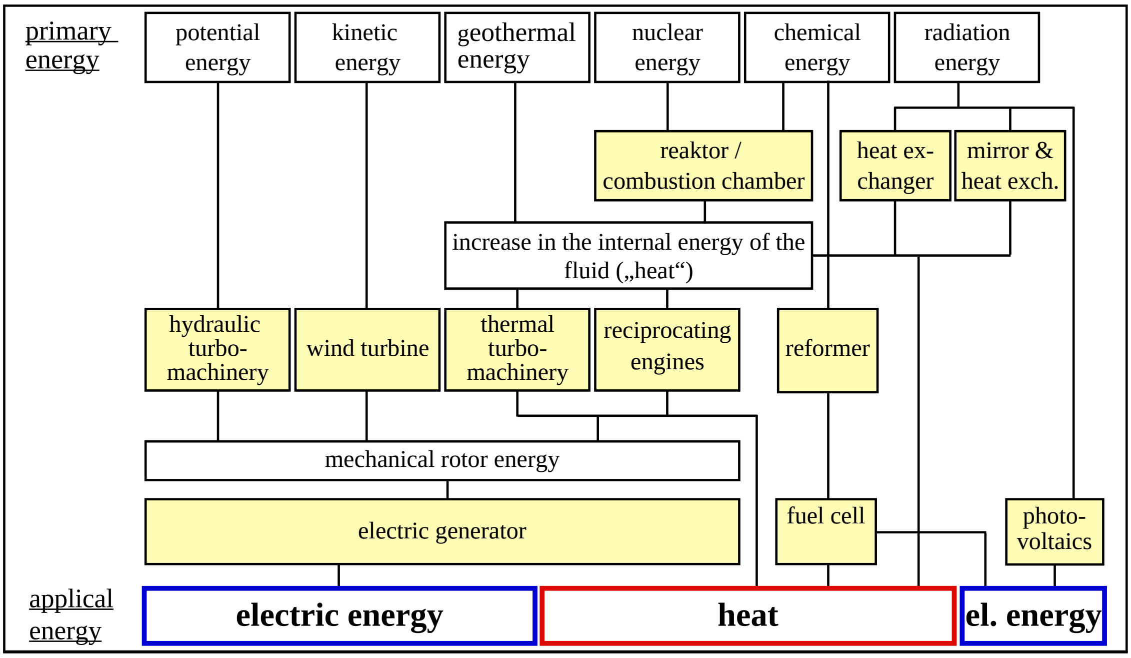

Figure 1.1: Kinds of energy and energy conversion technologies

Generating electric power using rotating machinery and combustion engines requires an additional generator to convert the mechanical energy. Combustion engines as well as thermal turbo machines convert the internal energy of fluids into mechanical energy. Depending on the primary energy sources, the increase of the internal energy is obtained in combustion chambers and reactors respectively, or by application of heat exchangers.

In principle, in all energy conversion processes increasing the internal energy of a fluid, heat is an integral part of the conversion chain. The processes only differ in the temperature level of the heat and the resulting use of heat. In the case of thermal turbo machines and combustion engines, the usable heat is available in the exhaust gas. For conversion of chemical energy in electrical energy by fuel cells, the heat necessary for the chemical reaction in the stacks can be used to provide usable heat too.

1.2 Share of energy sources

Regarding the electricity market, the proportions of the primary energy sources in the entire power generation in Europe (status: 2002) is shown in fig. 1.2. The structure of the energy source market in the different countries varies significantly to some extend. In the Netherlands, mainly fossil primary energy sources are used, whereas France is largely dependent on nuclear energy and Norway uses almost exclusively hydropower. Looking at all European countries, it becomes clear that the fossil energy carriers cover the main part of energy needs, with a total share of more than 50 %. Nearly the same can be stated for world wide primary energy utilization.

For ecological reasons, especially concerning the reduction of CO_2 emissions, it is aspired to increase the proportions of regenerative energy. To achieve this goal, the existing systems for utilization of regenerative energies should be expanded and improved. The investigations on new technologies and new concepts, in combination with an increase in the efficiency of systems for fossil primary energy carries, have to be supported.

Biogas, for example, can be used as a primary energy carrier in specially adapted micro gas

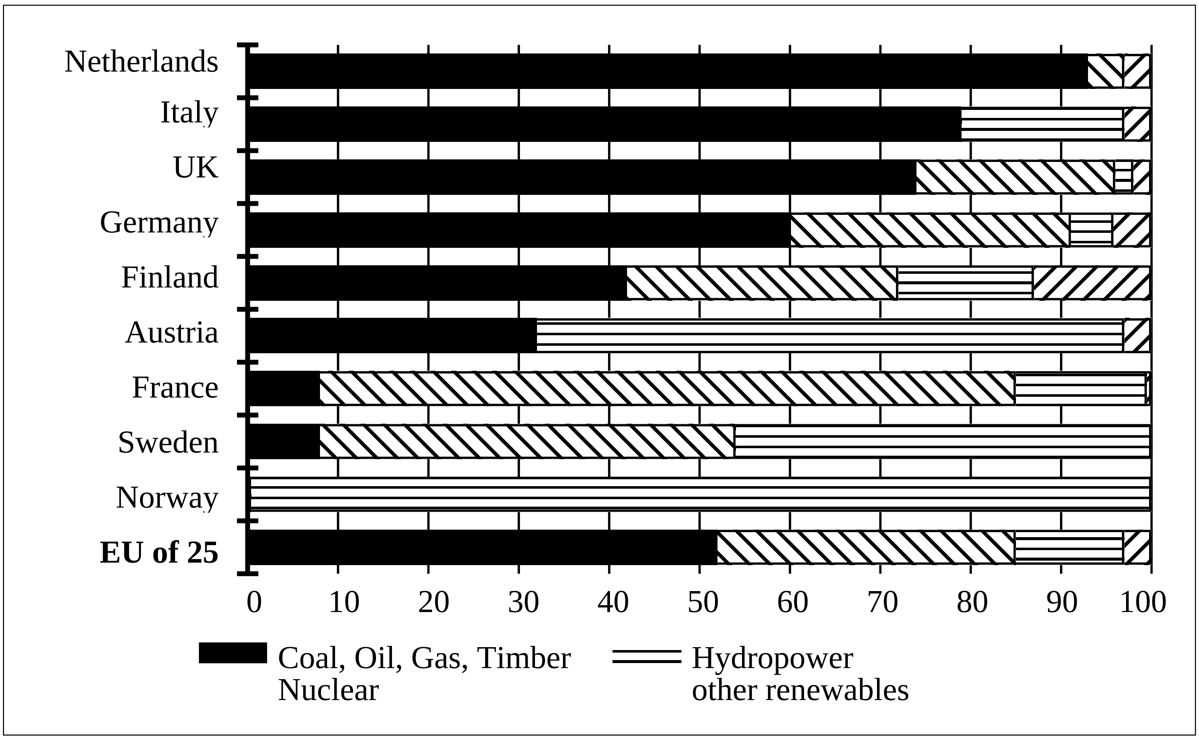

Figure 1.2: Share of Energy Sources on the total Power Generation (Status: 2002)

turbines. The field of application for micro gas turbines could the propulsion of motor vehicles, motor boats and small aircrafts like unmanned drones. Emergency power facilities and small, decentralized cogeneration units for combined supply of electric power and heat for housing and industrial estates can operate with micro gas turbines as well.

1.3 Structuring of the energy market

The main purpose of the energy market is to provide electricity and heat. In most countries the electricity market had a predominantly centralized structure, i.e. large facilities are used to generate electricity in power plants and distribute it by wires to the customer. Due to the higher losses when distributing heat over long distances, the heat market is in general decentralized in nearly all countries and regions. The heat supply is mainly produced by small units located near to the customers.

In the European Union (EU), it has been decided to deregulate the electric energy market. The different states of the the European Union have to realize this decision and are in progress different stages of transforming the market, in Great Britain, for example, the transformation was started very early whereas the electric energy market in France still is mainly centralized. Deregulation of the electricity market leads to the necessity of smaller energy conversion units that can provide both electricity and heat to the costumer. The market transforms to a decentralized market with new combined heat and power (CHP) units. The special motivation for the choice of such an innovative technology is, apart from reliable power supply, the opportunity to use the thermal energy for heating or for process-heat with a very high level of fuel utilization.

Both micro gas turbines (MGT) and fuel cells (FC) with an electric power range up to some 100 kW could be such units to cover the heat and electricity demands of residential estates and small industrial areas. Under populated regions could be energized by using MGTs and FCs with an electric power lower than 100 kW in stand-alone application. Especially in this application a very high reliability of the energy conversion system is demanded.

1.4 Requirements on innovative energy supply technologies

High flexibility for varying electricity and heat supply with constantly high fuel utilization belongs to the primary requirements for an economically attractive technology for decentralized electricity supply, especially if compared to coal or oil relatively expensive fuels such as natural gas are used. Furtermore, a high overall utilization of fuel leads to a great reduction in the emission of carbon dioxide.

A high degree of reliability and operation security belongs to the most important requirements for decentralized energy systems. Moreover, there is a need for multi-fuel options, which are very important for cost effective electricity and heat production with fluctuating fuel prices. If the technology is used for supplying private households or public buildings like schools or large office buildings with energy, a small power plant, a low noise and easy operation as well as low maintenance are essential features for the economic success of the technology.

The above-mentioned requirements are excellently fulfilled by micro turbines and hybrids that consist of a combination of a micro turbine and a high temperature fuel cell. These facilitate, due to their potential of electrical efficiencies of at least 75% for small units (< 200 kW), an environmentally good power supply with low carbon dioxide emissions, which at the same time saves energy resources. Another important factor is that gas turbines and fuel cells generate only very low amounts of toxic emissions such as NO_x or CO.

2. MICRO GAS TURBINES

Gas turbines use the chemical energy from fossil fuels to increase the internal energy of the working fluid in a combustor. This heat is converted by the turbine into mechanical energy that drives the compressor and the generator. A considerable amount of heat, which can be used for heating purposes or as process heat is available in the exhaust gases. This means that gas turbines are extremely suitable as combined heat and power systems (CHP) for decentralized energy supply.

It is common to distinguish between small and micro gas turbines. Both of them are suitable for the decentralized market, but it is difficult to indicate the exact separation between the two types. In this paper small gas turbines will be those with an electrical power output between 100 and 500kW. It must be mentioned, though, that there are only very few of these turbines available. Gas turbines with an electrical power output of less than 100 kW are classified as micro gas turbines. Many micro turbines are developed on basis of turbo chargers, which have nearly the same power range. Micro gas turbines are working with low pressure ratios between 3 to 1 and 7 to 1 and high rotational speeds.

Recently, several micro gas turbine with a power output of 20kW to 100kW have become available. Gas turbines with an electrical power output between 100kW and 300kW are either being developed or planned on being developed.

2.1 Manufacturers of micro gas turbines

The compact design distinguishes micro gas turbines from other technologies. Compared to engines micro gas turbines have a reduced complexity with less mechanical parts and no oscillating mass-forces.

2.1.1 Nissan

One of the smallest micro gas turbines for the generation of electricity is Nissan's DYNAJET 2.6. The power output of this machine is 2.6 kW and the rotational frequency is 100 000 rpm. The turbine is designed to be fuelled with Kerosene. In figure 2.1 the schematic diagram of the turbine and the generator is presented.

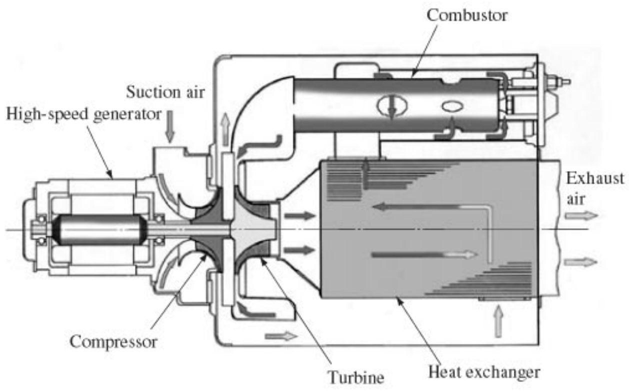

Figure 2.1: Nissan DYNAJET 2.6

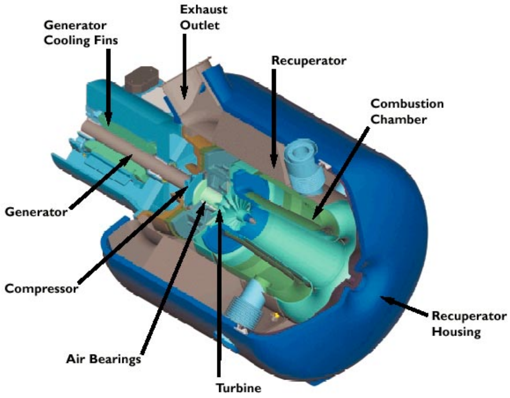

Figure 2.2: Capstone C30

2.1.2 Capstone

The Capstone C30 and C60 MicroTurbine have some special features compared to the Nissan turbine. Figure 2.2 contains a schematic of the C30 MicroTurbine. Capstone includes air bearings so that there is no need for an oil system; air bearings reduce the friction losses as well as the amount of maintenance. The power outputs are 30 kW (C30) and 60 kW (C60) and the exhaust temperature is 275 °C. Capstone delivers the C30 MicroTurbine for the usage of different types of fuel, like natural or propane gas and biogas. The C60 MicroTurbine is designed for natural gas only.

2.1.3 Other Manufacturers

The development as well as production and marketing of micro gas turbines primarily takes place in the USA and Japan, as above-mentioned Nissan and Capstone show. Other manufacturers are Elliot (100 kW CHP micro turbine), Ingersoll-Rand (MT70 and MT250) and Bowman. Bowman provides micro gas turbines from the Turbogen^{TM} family with a power output of 80 kW. All of these manufacturers are based in the USA.

In Europe Turbec (T100 micro turbine) is the only manufacturer that offers micro gas turbines. Turbec, previously owned by ABB and Volvo, was purchased in December 2003 by the Italian-based API Com srl.

2.2 Characteristics of Micro Gas Turbines

2.2.1 Process

In this chapter some characteristics of micro gas turbine systems are explained using the examples of the Capstone and Bowman MGTs. Both are designed for combined heat and power (CHP) applications and use a simple cycle with a recuperator to enhance the efficiency of the process.

In order to cover a wider range of the market for combined heat and power, Bowman offers with its TG80RC-G-R a micro gas turbine with a bypass to the recuperator (see figure 2.3). Because of this bypass the thermal output of the micro gas turbine can be varied between 136 kW_{th} (0% bypass) and 216 kW_{th} (50% bypass) while the electrical power output keeps constant at 80 kW_{el}. Bypassing the recuperator reduces the efficiency of the process from $\eta_{el} = 28\%$ at 0% bypass to $\eta_{el} = 22\%$ at 50% bypass (see figure 2.4). Bowman also offers, for CHP applications with a high thermal demand, the TG80SO-G micro gas turbine without recuperator. This micro gas turbine provides an exhaust gas temperature of 535°C and an electrical power output of 80 kW_{el}. The electrical net efficiency of this process is only 15,5%.

Other than Bowman, Capstone offers a micro gas turbine with a very compact design of the arrangement between generator, compressor, turbine and recuperator (see figure 2.2). The intake air is guided through the generator in order to cool it. A small loss in efficiency has to be taken for granted because of the raised temperature at the inlet of the compressor. The compressed air is preheated by the hot exhaust gas in the recuperator. This is arranged around the turbine and the combustion chamber, serving also as the casing of the system.

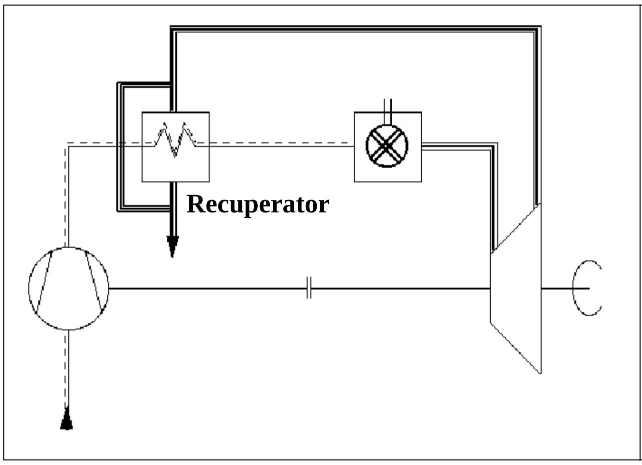

Figure 2.3: Process of the Bowman TG80RC-G-R

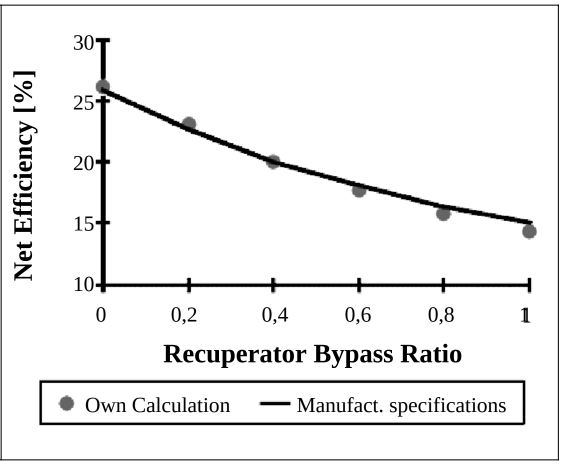

Figure 2.4: Efficiency at different Bypass Ratios

Due to this design, the heat losses in the turbine and the combustion chamber can be reduced significantly, leading to a higher net efficiency.

Kawasaki Heavy Industries has been active in the field of small gas turbines and developed, in the framework of the New Sunshine Project, a gas turbine with an electrical power output of 300 kW. The process parameters of this prototype like the turbine inlet temperature could be increased significantly by using ceramic components (see also chapter 2.3).

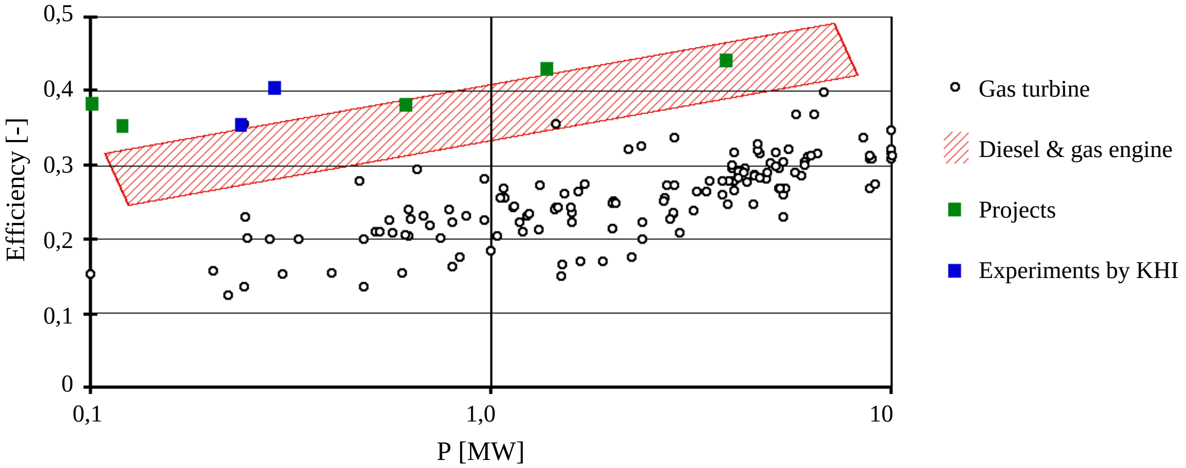

Figure 2.5: Net efficiency of gas turbines and motors depending on the power range

2.2.2 Comparison of small and micro gas turbines with motors

Small and micro gas turbines and diesel- and gas-engines are designed for similar applications. Although the efficiency of today's gas turbines is lower than the efficiency of diesel- and gas-engines (see figure 2.5), in recent times several projects have demonstrated the future potential of gas turbines. The development of gas turbines reaching net efficiencies of up to 40%, thereby diminishing the difference between gas turbines and motors, seems possible within the next couple of years.

A further advantage of gas turbines compared to motors are the significant lower pollutant emissions, especially toxic gases like NO_x and CO. While todays diesel engines produce NO_x-emssions of 100-200 ppmv, in gas turbines NO_x-emissions lower than 25 ppmv can be reached due to the lean-premix combustion without the need of secondary methods. Furthermore, "single digit"-burners are currently under development and a further potential for decreasing the pollutant emissions can be found in the catalytic combustion.

2.2.3 Market requirements

The well-engineered gas turbines of larger power output that are on the market are characterized by their high availability and reliability, simple and robust design, low-maintenance, a life-span of more than 100 000 operating hours. If micro gas turbines are expected to be marketed successfully they must fulfill these demands in the future. The Mach number effect can be scaled down while the Reynolds number effect cannot. It leads to a reduced efficiency of small and micro gas turbines. The disadvantages concerning the efficiencies can be compensated by the above-mentioned improvements.

2.3 Main Components

Micro gas turbines that have been developed up till now have an electric power output between 20 and 100 kW. Using present-day technology the efficiency of gas turbines with recuperator in this output class is approximately 26%. Current research- and development projects in this output class aim to rise the efficiency in recuperated processes to over 35 % - 40 %. This call for an improvement of the turbine inlet temperature as well as an improvement of the components efficiency in the future.

The sensitivity with which a micro gas turbine of the 80kW-class reacts to changes in the defining parameters (e.g. temperature) will be investigated in the following /2/. The turbine inlet temperature is 950 °C, the pressure ratio 4.5 and the efficiency of the recuperator 85%, that of the compressor 79% and that of the turbine 84%. The fuel gas pressure is approximately equal to the ambient pressure. The influence of the fuel gas compressor efficiency on the design for different pressure ratios of the compressor is taken into account.

In fig. 2.4 the dependance of the specific work and of the efficiency of the micro gas turbine on the thermodynamic process parameters is depicted. The design point of a micro gas turbine with state-of-the-art technology is indicated.

As can be seen on the right side of fig. 2.6 an increase of the turbine inlet temperature up to 1500°C leads to a substantial improvement of the efficiency (approximately 20 % - 25 %) and the specific work (approximately 100 %). Therefore, the increase of the turbine inlet temperature for micro gas turbines is the target of further developments. Because of the small dimensions of micro gas turbines it is not possible to use cooling technology to be able to increase the inlet temperature. It means that such an increase can only be realized by applying new materials.

Additional potential for efficiency improvements lies with increasing the efficiency of the components such as the turbine, the compressor, the combustor and the recuperator.

The analysis is summarized in fig. 2.7. In comparison with the previous figure the electrical efficiency of the system instead of the thermal efficiency is shown. Additional losses results from the bearing, the generator and the conversion of the frequency. Especially when concerning the bearing there is a large potential for improvements by using oil-free bearings, such as air bearings and magnetic bearings. Compared to conventional oil bearings, the air bearing have reduced losses. An additional advantage of them is less maintenance. Furthermore, in case the MGT is coupled with a fuel cell, it is not possible that oil in the exhaust can lead to problems in the fuel cell due to leakages.

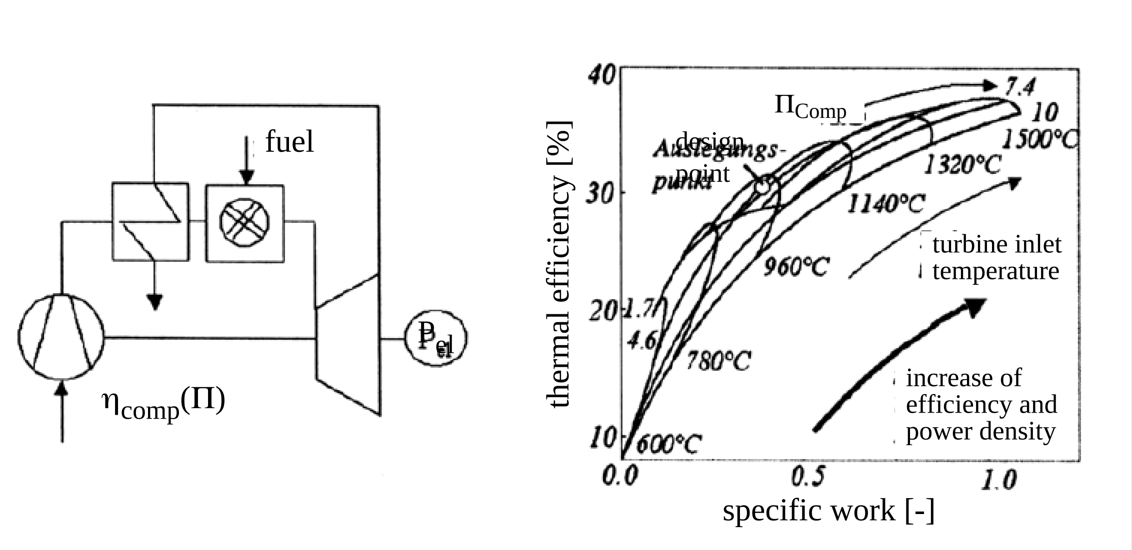

Figure 2.6: Schematic of a micro gas turbine and influences of the thermodynamic parameters on the efficiency and the specific work /2/

The long-term potential for the net efficiency of micro gas turbines is marginally higher than 42 % when the fuel gas pressure is similar to the ambient pressure and without a gas compressor circa 44 %.

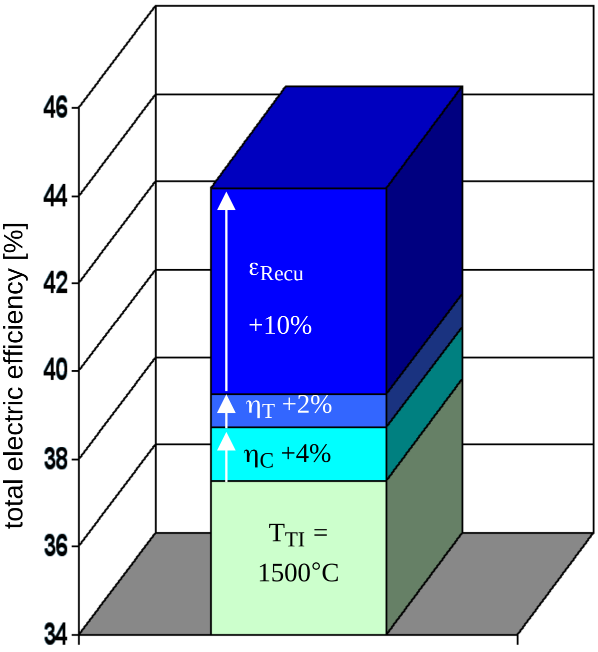

Figure 2.7: Improvements of the efficiency of micro gas turbines

2.3.1 Turbine

At conventional turbine inlet temperatures high durability and temperature resistance can only be achieved by using nickel-base alloys. The application of those alloys is state-of-the-art. Temperatures up to *950 °C* can be realized in micro gas turbines. Higher temperatures

material	thermal expansion	thermal conductivity	max. operating temperature	remarks
SiC	3,9-5,0·10^{-6} 1/K	80-150 W/(mK)	approx. 1200°C	
Si_3N_4	2,0-3,5·10^{-6} 1/K	15-45 W/(mK)	approx. 1200°C	
fiber-reinforced. Si_3N_4: C-, SiC-, TiB_2-fiber	2,0-4,0·10^{-6} 1/K	15-90 W/(mK)	approx. 1400°C	high oxidation-sensitivity of the fibres
Ni alloys (for comparison)	11,5-13,5·10^{-6} 1/K	15 W/(mK)	approx. 900°C	

Table 2.1: Characteristics of Ceramic Materials

can only be reached by usage of ceramic materials. Here, only non-oxide ceramics are to be considered, e.g. fiber-reinforced Si_3N_4 /3/ or 5-20 % SiC-reinforced Si_3N_4 /4/, which have higher strength durability than pure Si_3N_4. Due to those materials turbine inlet temperatures up to 1400 °C are possible in principle. A sufficient stability of those materials against oxidation in an environment consisting of exhaust gas of liquid or gaseous fuels is yet to be proven.

The characteristics of ceramic materials are listed in table 2.1. An additional potential in the field of high temperature materials was presented by /5/ (fig. 2.8). Figure 2.9 shows the Kawasaki CGT302 with the included ceramic components. The stated efficiency of this experimental machine is 42% with a power output of 300kW. Up to now there is no derived application for the market. Figure 2.10 shows the predictions on several steps in the development of GTs and, connected with this, their efficiency. This estimation is made at 2000. From the current view, it seams the estimation is a bit of optimistic.

2.3.2 Recuperator

For conventional turbine inlet temperatures of 950 °C, the temperature at the hot side inlet of the recuperator is about 600 °C. For raised turbine inlet temperatures of 1400 °C the recuperator inlet temperature is increased to approximately 1000 °C. This makes the application of high-temperature materials such as ceramic materials essential. Due to its good heat conductivity, SiC should be preferred. A sufficient durability of the heat exchanger and a high resistance against erosion and oxidation must be proven. Due to the low tolerance of ceramics regarding tensile stresses, particularly in the case of comparatively large components like heat exchangers, this kind of load is to be minimized.

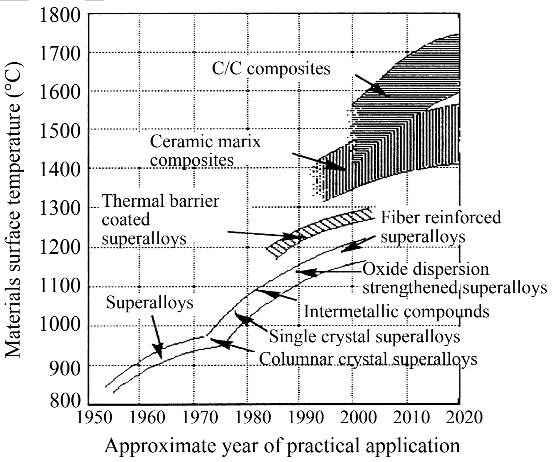

Figure 2.8: High temperature materials /5/

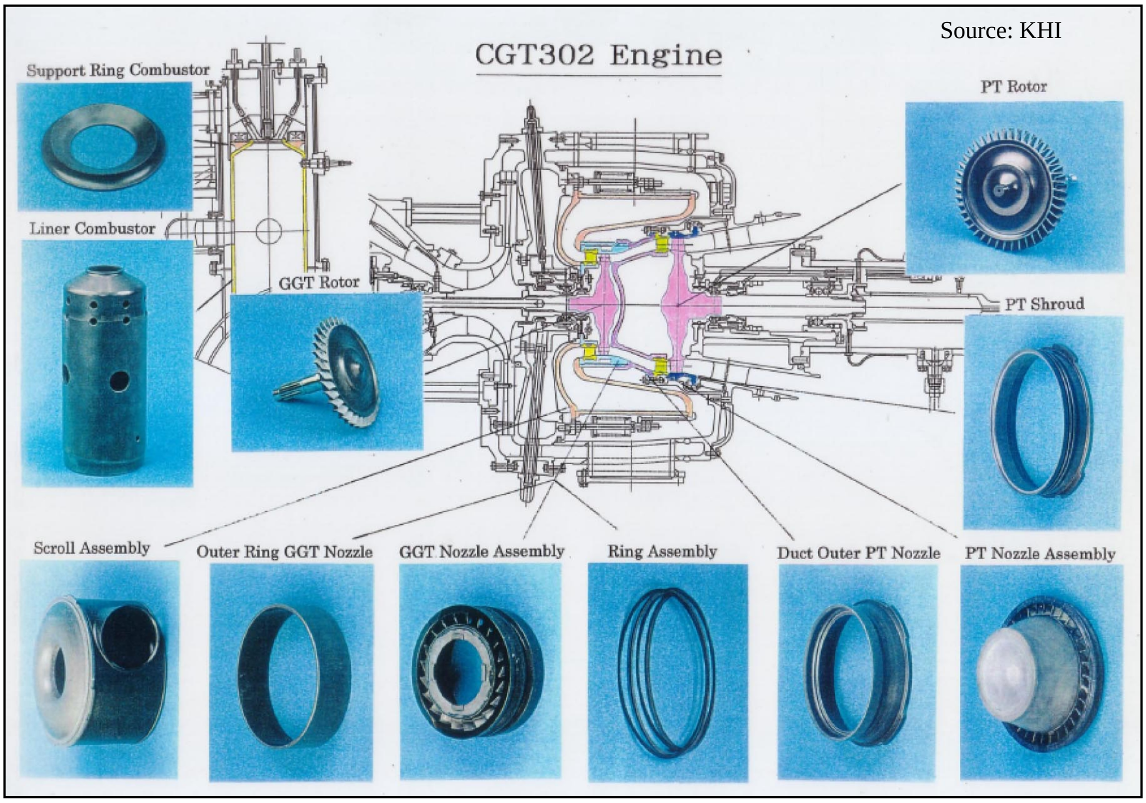

Figure 2.9: Ceramic components of the CGT-302 gas turbine

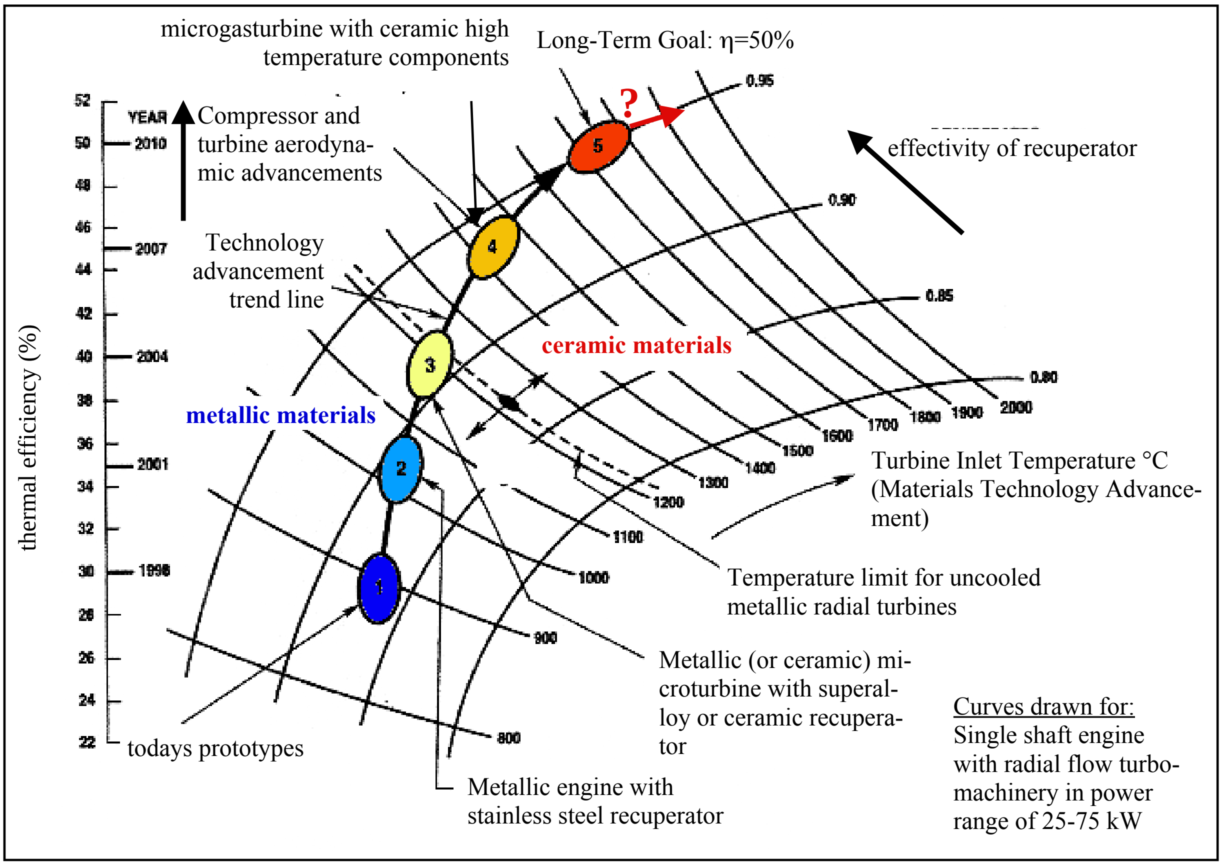

Figure 2.10: Predictions of development of micro turbine technology /6/

2.3.3 Shaft

For conventional gas turbine inlet temperatures, a metal-based shaft design is possible. At higher turbine inlet temperatures, high-temperature nickel-base alloys or ceramic materials have to be used. For a 30 kW_{el} micro gas turbine the force-fit connection between the shaft and the compressor blade wheel, the turbine blade wheel and the generator has to transfer a power of 100 to 150 kW.

The connection between the a shaft of nickel-base alloy and a ceramic turbine blade wheel has to be designed in a way that creates a uniform force transmission and avoids any stress peaks within the ceramic material. For this application multi-layer activated silver soldering is basically suitable, but this materials are up to now limited due to their temperature stability of about 480 °C /7/.

As an alternative, the shaft and the turbine wheel could be manufactured as one part. In such a design, the junction between wheel and shaft could be designed in a way which avoids stress peaks. Producing a ceramic shaft able to resist the resulting forces will be the most important challenge. For the force-fit connection of the ceramic shaft and the compressor blade wheel, multi-layer activated silver soldering may be possible without any problems because of the lower temperatures compared to the hot turbine region.

2.3.4 Bearings

The losses of oil lubricated bearings in exhaust-gas turbochargers reach 10-15 % of the turbine power /8/. In micro gas turbines of the aforementioned size, losses of 4-7 % have to be expected. By using oil lubricated bearings in micro gas turbines, the necessary periphery (Oil cooler, oil pump, sedation pipe) have to be provided. Additionally, a recurrent change of the oil is necessary, which leads to a higher maintenance effort.

A solution with minor losses as well as lower maintenance efforts is possible by using air bearings or magnetic bearings.

Air bearings are not sensitive concerning the bearing temperatures. In micro gas turbines they could be provided with compressed air from the compressor. Manufacturer instructions specify an air requirement of 2 g/s /9/ at 5 bars for the bearing forces, which have to be expected in micro gas turbines. At lower pressure ratio of the gas turbine, the requirement of air will increase marginally. One example for a the application of an air bearing in a micro gas turbine is the Capstone C30.

Magnetic Bearings achieve a stabilization of the rotor position by a vertically as well as horizontally aligned magnetic field. An active measurement of the rotor position is essential for holding the rotor position and the dampening of eventually upcoming rotor oscillations. The usability of magnetic bearing for micro gas turbine rotors are restricted by the Curie-point, which is between 350 °C and 450 °C for most metals. No magnetization of the material occurs above this temperature. Therefore, the basic principle of those bearings fails. For special metals, magnetic characteristics can be maintained up to temperatures of 650 °C /10/. Additionally, the electrical resistance of the coils increases at higher temperatures. A high temperature insulation (e.g. ceramics /10/) has to be provided for the coils. Therefore, the application of magnetic bearing is based on the development of high temperature magnetic materials, low-loss coils, high temperature insulations and the integration of bearing cooling technologies. *Field and Iannello*/11/ report on a magnetic bearing which was designed for turbomachinery application and tested for temperatures up to 427 °C.

2.3.5 Gear system

The high frequency of the micro gas turbines (up to 1500-2000 Hz) must be converted to the commercial frequency of 50/60Hz by gear systems. Most of the above-mentioned manufacturers integrate a single shaft turbinedesign with an electronic gear box. A schematic overview of the electronic gear box of the Capstone C30 micro gas turbine is shown in Fig. 2.11. Only Ingersoll-Rand install a mechanical gear box to reduce the rotational frequency and to connect the shaft to the generator.

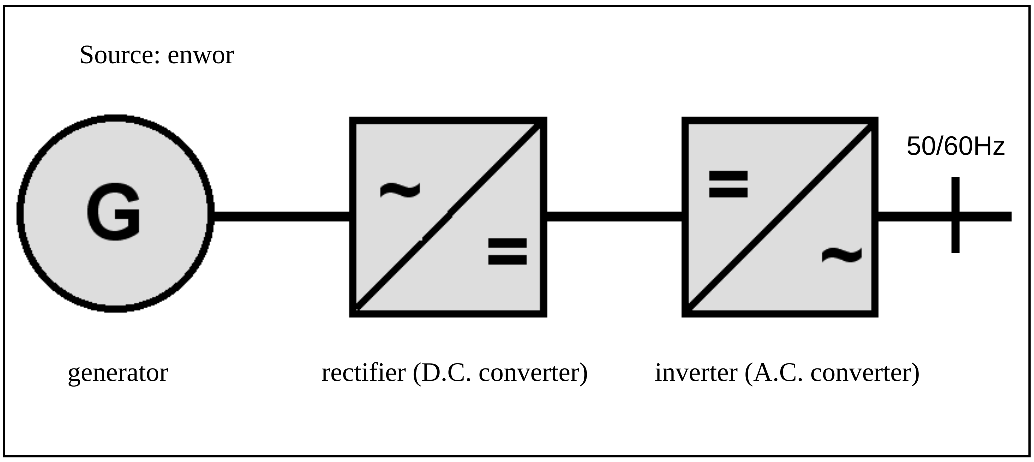
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Figure 2.11: Schema of an electronic gear box

Compared to the mechanical version the electronic gear box reduce both losses and the complexity of the machine. Because the generator is mechanically decoupled from the commercial frequency, the rotational frequency of the turbine can be varied. This leads to a better efficiency in the part load region.

2.4 Multi Fuel Capability for Micro Gas Turbines

For micro gas turbines for small sized plants it becomes an increasingly important feature to be able to burn apart from natural gas also low-BTU biogenous fuel. This feature is especially important for micro gas turbines for decentralized applications.

Biogenous fuels and waste gases will probably contribute substantially to future power generation. These low-BTU fuels can reduce the dependence on fossil fuels in the future and support international efforts to reduce CO_2-emissions.

If the fuel is directly fired in the gas turbine combustor modification of the gas turbine technology are required to be able to cope with non-standard fuel constituents and non-standard heating values. Depending on the fuel type, these modifications reach from the application of corrosion resistant materials to modifications of the design of gas turbine components /12/, /13/.

2.4.1 Overview over Low-BTU Gaseous Fuels

Because low-BTU gases originate from different methods of conversion they have different major combustible components. Anaerobic digestion produces gases with high methane and carbon dioxide content. Thermal gasification produces gases with high concentrations of hydrogen and carbon monoxide (see Table 2.1). Further constituents of the fuel-gases, like sulfur, chlorine, and alkali metals require the application of special materials in the gas turbine and/or fuel treatment.

Fuel	CH4	CO2	N2	O2	CO	H2	others
natural gas	97,9	0,1	1	-	-	-	1
biogas	65,3	34,4	-	-	-	-	0.3 (H_2S)
sewage gas	60	32	5	-	-	3	-
coke-oven gas	31	1,2	1,5	1	7	55	3,3
landfill gas	52,5	37,8	7	1	-	0,27	1,43
mine gas (with dilution air)	45	2,5	42	10	0	0,1	0,4
wood gas	1,5	9,1	53,2	-	19,2	17	-
blast furnace gas	-	19.5	55	-	20.9	4.6	-

Table 2.1: Average compositions of dry low-BTU gases in [Vol-%] /14/

Fuel	Fuel Heating Value (MJ/Nm^3)**	WI/ WI_{NG}	average adiabatic flame temperature* in Kelvin
natural gas	38,5±6,0	1,0	2547
biogas	23.0±3.0	0.472	2425
sewage gas	19.0±2.0	0.394	2417
coke-oven gas	17.0±0.5	0.576	2633
landfill gas	16.5±3.0	0.325	2376
mine gas (with dilution air)	16.0±5.0	0.344	2520
wood gas	5.3±1.0	0.110	2126
blast furnace gas	3.7±1.0	0.070	1801

*: Combustor Inlet Temperature 600K, Equiv. Ratio=1.0 (dissociation is neglected)
**: Nm^3 = cubic meters at standard conditions

Table 2.2: Average heating values and adiabatic flame temperatures of low-BTU fuels /14/

When adaptating gas turbine combustors, fuel system, and fuel-gas boosters to low- and medium-BTU fuels one has to take into account that the fuel mass flow for constant input increases and that the Wobbe-Index of low-BTU fuels is lower than that of natural gas. The heating values, Wobbe-Indices, and adiabatic stoichiometric flame temperatures of medium and low-BTU gases are listed in Table 2.2.

2.4.2 Effect of Biogas Untilization on Micro Gas Turbine Operation

Operation of the micro gas turbine on biogas instead of natural gas leads to a shift of it's operating point as it is shown in Fig. 2.12. Major control parameters of the micro turbine system are power output, rotational speed, and turbine outlet temperature /15/. The rotational speed is kept constant for stand-alone operation. In part-load operation in grid-connected mode an operation point that produces the optimum efficiency at a given turbine inlet temperature is chosen /15/.

When natural gas is replaced by biogas two diffrent control methodes that leave the electrical power output a free variable can be considered /14/:

1. Constant turbine inlet temperature (CASE A),
2. Constant energy input to the combustor (CASE B).

Figure 2.13 shows the effect of both control methods on the machine pressure ratio and efficiency. A large range of methane contents was considered in order to account not only for standard quality biogas, but also for poor quality gas. A methane content of 100% corresponds to natural gas. It can be seen that an increase of the pressure ratio occurs if the turbine inlet temperature is kept constant. This is due to the increased volumetric flow in the turbine. The investigated micro gas turbine reach the surge margin for very low contents of methane (around 15%), which is much lower than the methane content found in average biogases. Increased carbon dioxide contents and reduced methane contents lead to a reduction of air mass flow in the combustor. This is shown in Fig. 2.14.

Case B shows that keeping the energy input to the combustor constant leads to a reduction of inlet temperature and hence to a reduction of the volumetric flow in the turbine. The consequence of this is drop in the pressure ratio at the turbine. Therefore no operating conditions that are critical for the compressor are observed.

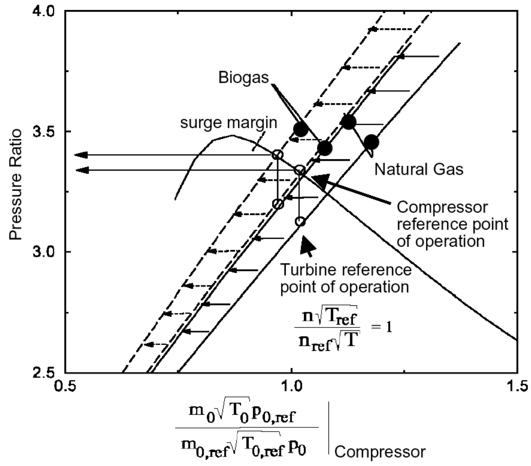


Figure 2.12: Influence of biogas combustion on the operating points of micro turbine compressor and turbine (index '0': inlet conditions) /14/

For standard quality biogas a decrease of efficiency by approximately 0.6 percentage points occurs in case A, whereas case B leads to a decrease by 1.1 percentage points (see Fig. 2.13).

2.4.3 Sources of Pollutant Emissions from Combustion of low-BTU Fuels

Although emissions of nitrogen oxides decrease with reduced maximum flame temperatures for most low-BTU fuels, some non-standard constituents and properties of these fuels lead to additional pollutant emissions and/or corrosion, erosion and plugging of gas turbine components.

The increased mass flow leads to reduced residence times in the combustor and this in combination with the reduced temperature, increases carbon monoxide emissions from the combustor. This implies at the same time a decrease in combustion efficiency. This problem can be overcome by resizing the

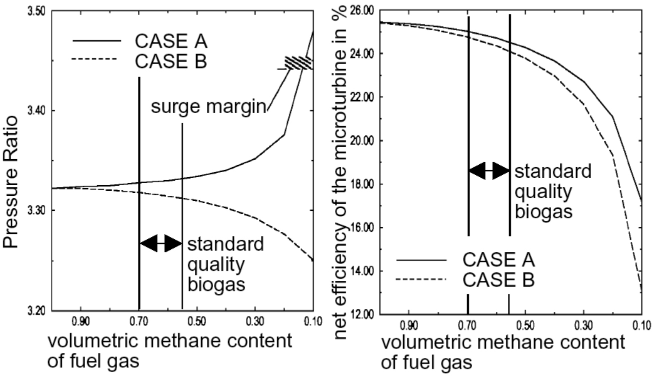


Figure 2.13: Pressure ratio and net efficiency of micro turbine firing biogas /14/

combustor and/or intensifying the hot gas recirculation for flame stabilization can achieve an increase in combustor residence times. The safe destruction of chlorinated polycyclic hydrocarbons requires temperatures above 1120 Kelvin /16/, therefore they should be removed from the fuel gas prior to combustion. At elevated temperatures of approx. 1020 Kelvin alkaline sulfates are formed due to alkali metals. The resulting sulfur oxides in exhaust gases exhibit a highly corrosive character. As sulfur dioxide is toxic for the environment as well, all sulfur should be removed from the fuel gas. If the particles in fuel gases exceed the manufacturer's specifications for particle concentrations it can lead to plugging of the fuel supply system. Therefore these concentration should be monitored carefully.

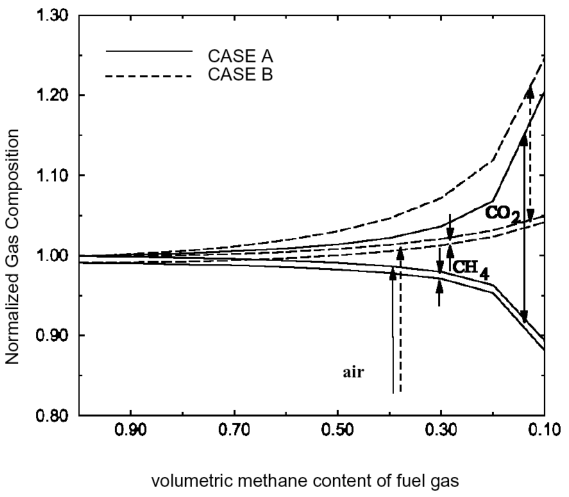


Figure 2.14: Normalized gas composition at combustor inlet /14/

2.5 Market of the Distributed Power Supply

In the year 2000 experts from German power suppliers were interviewed by *team steffenhagen GmbH marketing research & consulting* about the future energy market. They estimated at that time that the market share of distributed power supply will reach 25% in 2015 from 10% in 2000 (fig. 1.3). This means that this market is expected to increase by 15% points within the following 15 years. 80% of the distributed power will be supplied by fuel cells, MGTs or MGT/FC hybrid systems, as shown in fig. 2.16.

2.6 Conclusion

Due to the changes in the electricity market small units providing both heat and power (CHP) like micro gas turbines and fuel cells will become more important. Therefore, in order to be successful in the decentralized market, the new technologies on MGT or MGT/FC hybrid system should be paid more attention to. The electrical effciency of micro gas turbines as well as the standards of operation, however, have to be improved to a more competitive level. Micro gas turbines have a good potential to increase the efficiency by using ceramic components as shown by the Kawasaki CGT 302.

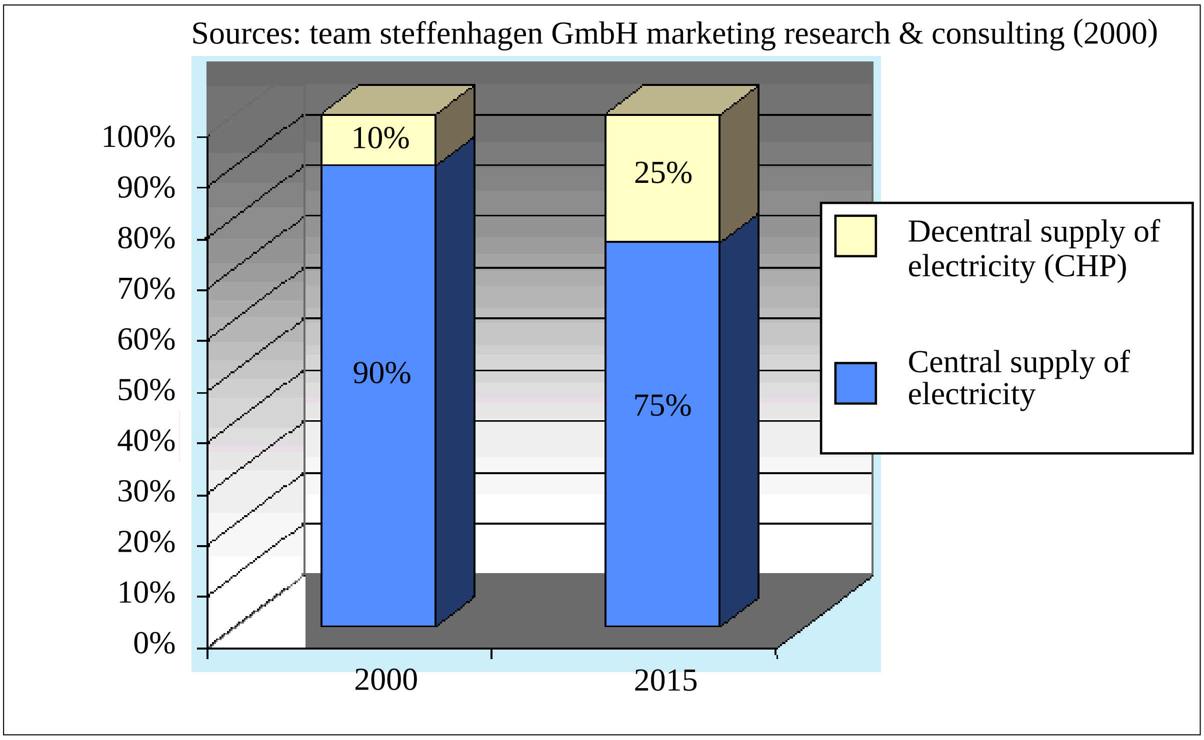


Figure 2.15: Estimated Power Supply in 2015

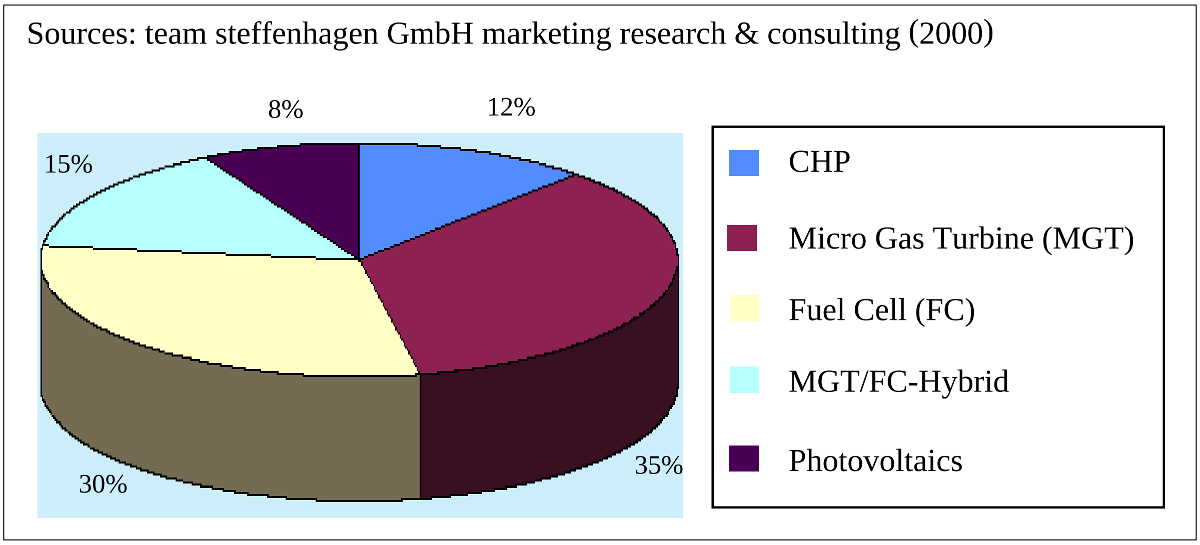


Figure 2.16: Decentral Power Supply in 2015

3. FUEL CELL

Hydrogen is a promising energy carrier. It is the most common chemical element on the planet and can be produced from diverse domestic resources, water, natural gas, biomass etc. Its conversion to heat and power is simple and clean. When combusted with oxygen, hydrogen forms water; no pollutants are generated or emitted. The water is returned to nature where it originally came from. Such a process is quite efficient and reliable. Therefore hydrogen is expected to become a renewable energy that will replace the traditional energy carriers.

3.1 History of Fuel Cell

As early as 1839, Sir William Grove (often referred to as the "Father of the Fuel Cell") discovered that it may be possible to generate electricity by reversing the electrolysis of water. His scheme is shown in Fig. 3.1 /17/. It was not until 1889 that two researchers, Charles Langer and Ludwig Mond, coined the term "fuel cell" as they were trying to engineer the first practical fuel cell, using air and coal gas. While further attempts were made in the early 1900s to develop fuel cells that could convert coal or carbon into electricity, the advent of the internal combustion engine temporarily quashed any hopes of further development of the fledgling technology.

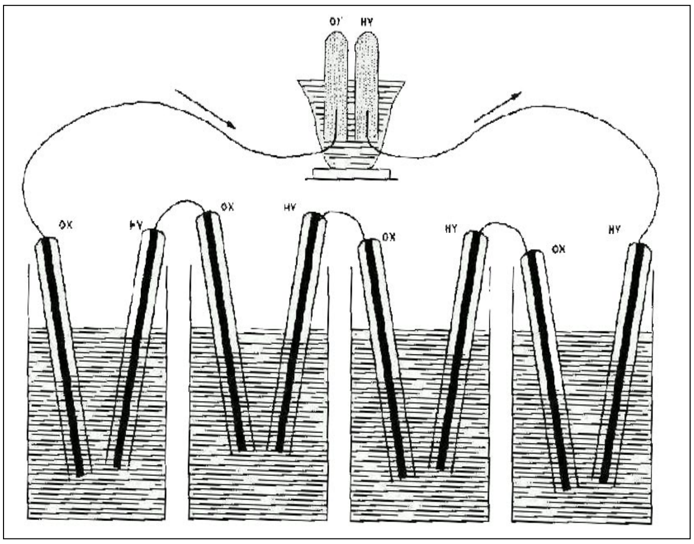


Figure 3.1: Four Cells of Crove's Battery to Drive an Electrolytic Cell /17/

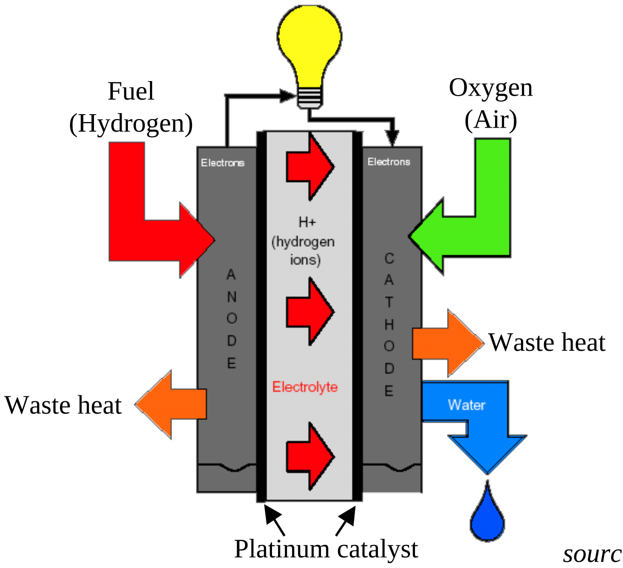
Francis Bacon developed what was perhaps the first successful fuel cell device in 1932, with a hydrogen-oxygen cell using alkaline electrolytes and nickel electrodes - inexpensive alternatives to the catalysts used by Mond and Langer. Due to a substantial number of technical hurdles, it was not until 1959 that Bacon and company first demonstrated a practical 5kW fuel cell system. Harry Karl Ihrig presented his now-famous 20-horsepower fuel cell-powered tractor that same year.

In the late 1950s NASA also began to build a compact electricity generator for use on space missions. NASA soon came to fund hundreds of research contracts involving fuel cell technology. Now, fuels cells have a proven role in the space program, after having supplied electricity during several space missions.

In more recent decades, a number of manufacturers - including major automobile manufacturers - and various federal agencies have supported ongoing research into the development of fuel cell technology for the use in fuel cell vehicles (FCV) and other applications. Fuel cell energy is now expected to replace traditional power sources in coming years - from micro fuel cells to be used in cell phones to high-powered fuel cells for stock car racing.

3.2 Basic Principle of Fuel Cell

Fuel cells are electrochemical devices that combine hydrogen fuel and oxygen to produce electricity, heat and water. This common feature defines all fuel cells, regardless of the type of fuel cell. As described in the Fig. 3.2, an electrolyte separates two electrodes: an anode and a cathode. Hydrogen enters the anode, while oxygen from the air passes into the cathode. A catalyst splits the hydrogen into a proton and an electron. The protons travel through the electrolyte to the cathode. The electrons cannot pass through the membrane, so they must flow through an external circuit, creating a DC circuit. The electrons finally arrive at the cathode as well, where they recombine with the hydrogen and oxygen. Heat and water are thus produced. A fuel cell is made up of "stacks" of numerous electrode / electrolyte "cells".



source: LAGANEnergy

Figure 3.2: Basic Principle of Fuel Cell Technology

3.3 Types of Fuel Cells

Fuel cells are classified primarily according to the kind of electrolyte they employ. This determines the kind of chemical reactions that take place in the cell, the kind of catalysts required, the temperature range in which the cell operates, the fuel required, and other factors. These characteristics, in turn, affect the applications for which these cells are most suitable. There are 5 major types of fuel cells currently under development:

- Alkaline (AFC)
- Proton Exchange Membrane (PEMFC)
- Phosphoric Acid (PAFC)
- Molten Carbonate (MCFC)
- Solid Oxide (SOFC)

Each type has its own properties, advantages, limitations and applications, as listed in Tab. 3.1. It is obvious from the temperature ranges that, whereas pressurized FC's operate at intermediate temperatures, aqueous electrolytes are used mostly in the low-temperature range.

- **Alkaline Fuel Cells**

Alkaline fuel cells (AFCs) were one of the first fuel cell technologies developed, and they were the first type widely used in the U.S. space program to produce electrical energy and water on-board spacecraft. These fuel cells use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode. High-temperature AFCs operate at temperatures between 100°C and 250°C . Newer AFC designs, however, operate at lower temperatures of roughly 23°C to 70°C

- **Proton Exchange Membrane (PEM) Fuel Cells**

Proton exchange membrane (PEM) fuel cells—also called polymer electrolyte membrane fuel cells—deliver a high power density and offer the advantages of low weight and volume compared to other fuel cells. PEM fuel cells use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum catalyst. They need only hydrogen, oxygen from the air and water to operate and do not require corrosive fluids like some other fuel cells. They are typically fueled with pure hydrogen supplied from storage tanks or on-board reformers.

- **Phosphoric Acid Fuel Cells**

Phosphoric acid fuel cells use liquid phosphoric acid as an electrolyte—the acid is contained in a Teflon-bonded silicon carbide matrix—and porous carbon electrodes containing a platinum catalyst. The phosphoric acid fuel cell (PAFC) is considered to be the "first generation" of modern fuel cells. It is one of the most mature cell types and the first to be used commercially. This type of fuel cell is typically used for stationary power generation, but some PAFCs have been used to power large vehicles such as city buses.

- **Molten Carbonate Fuel Cells**

Molten carbonate fuel cells (MCFCs) are currently being developed for natural gas and coal-based power plants for electrical utility, industrial, and military applications. MCFCs are high-temperature fuel cells that use an electrolyte composed of a molten carbonate salt

Table 3.1: Type of Fuel Cell and Properties

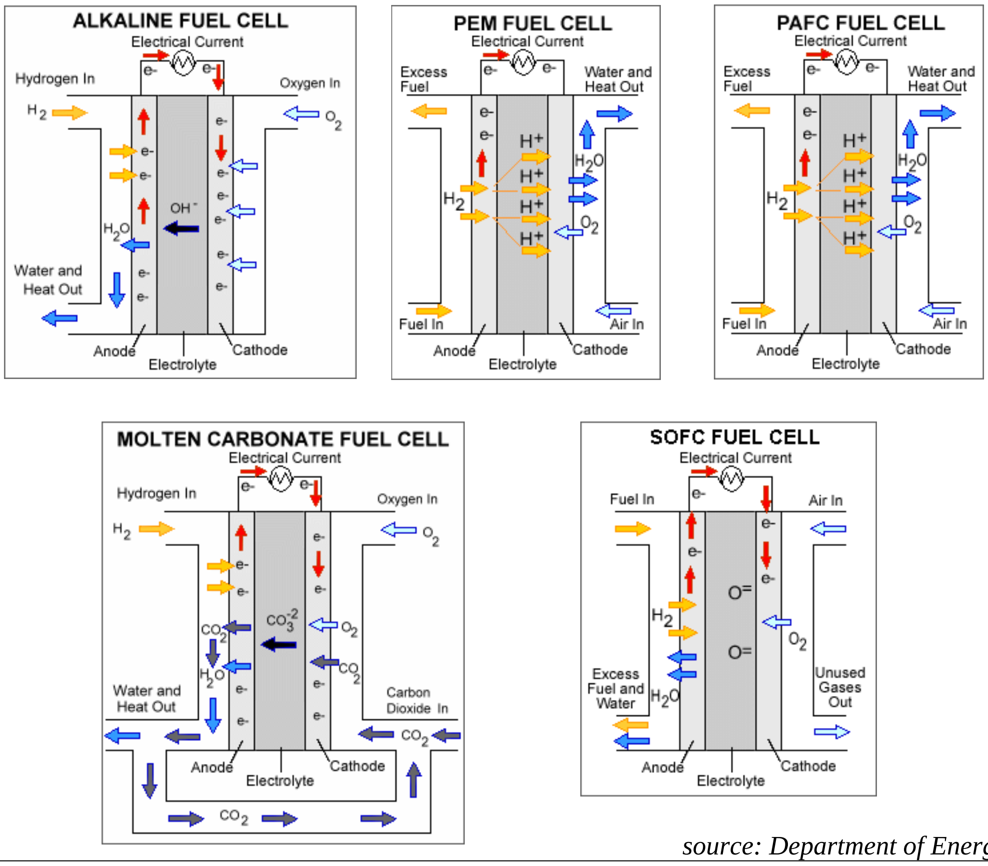
Fuel Cell Type	Operating temperature	Efficiency	Electrolyte	Advantageous	Disadvantageous	Applications
Alkaline Fuel Cell (AFC)	60-70 °C	36%	Aqueous solution of potassium hydroxide soaked in a matrix	• Cathode reaction faster in alkaline electrolyte - so high performance	• Expensive removal of CO_2 from fuel and air stream required	• Military • Space
Proton Exchange Membrane Fuel Cell (PEMFC)	85-105 °C	40%	Solid organic polymer poly-perfluorosulphonic acid	• Solid electrolyte reduces corrosion & management problems • Low temperature • Quick start-up	• Low temperature requires expensive catalyst • High sensitivity to fuel impurities	• Electric utility • Portable power • Transportation
Phosphoric Acid Fuel Cell (PAFC)	160-220 °C	40-45%	Liquid phosphoric acid soaked in a matrix	• Up to 85% efficiency in cogeneration of electricity and heat • Impure H_2 as fuel	• Requires platinum catalyst (expensive) • Low current and power • Large size/weight ratio	• Electric utility • Transportation
Molten Carbonate Fuel Cell (MCFC)	600-660 °C	47-45%	Liquid solution of lithium, sodium and/or potassium carbonates, soaked in a matrix	• High temperature advantages • Fuel Flexibility • Can use a variety of catalysts	• High temperature enhances corrosion and breakdown of cell components	• Electric utility
Solid Oxide Fuel Cell (SOFC)	900-1100 °C	48-55%	Solid zirconium oxide to which a small amount of ytrria is added	• High temperature advantages • Fuel Flexibility • Can use a variety of catalysts • Solid electrolyte reduces corrosion and management problem • Quick Start-up	• High temperature enhances corrosion and breakdown of cell components	• Electric utility

mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide ($LiAlO_2$) matrix. Since they operate at extremely high temperatures of 650°C and above, non-precious metals can be used as catalysts at the anode and cathode, reducing costs /18, 19/.

- **Solid Oxide Fuel Cells**

Solid oxide fuel cells (SOFCs) use a hard, non-porous ceramic compound as the electrolyte. As the electrolyte is a solid, the cells do not have to be constructed in the plate-like configuration typical to other types of fuel cell. SOFCs are expected to be around 50-60 % efficient at converting fuel to electricity. In applications designed to capture and utilize the system's waste heat (cogeneration), overall fuel utilization efficiencies could top 80-85% /18, 19/.

Solid oxide fuel cells operate at very high temperatures—around 1,000°C. High temperature operation removes the need for precious-metal catalysts, thereby reducing costs. It also allows SOFCs to reform fuels internally, which enables the use of a variety of fuels and reduces the costs associated with adding a reformer to the system.



source: *Department of Energy, US*

Figure 3.3: Illustration of the Chemical Reaction in Five Major Fuel Cells

In addition to the five major fuel cells listed above, the Direct Methanol Fuel Cell (DMFC) is being developed to tackle the fuel storage problem associated with the use of hydrogen. It also eliminates the need for a reformer to convert methanol, which a hydrogen fuel cell needs to work. The Direct Methanol Fuel Cell could also be classified as a Proton Exchange Membrane Fuel Cell (PEMFC), because it also uses a PEM membrane. However, in addition to platinum, other catalysts like ruthenium (Ru) have to be added to break methanol bond in the anodic reaction.

Figure 3.3 illustrate the chemical reactions in 5 major types of fuel cells. Table 3.2 lists the detailed chemical reaction equations inside the anode, cathode and electrolyte.

Table 3.2 Chemical Reaction Equations in Five Major Fuel Cell

Type	Chemical Equations		
	Anode:	Cathode	Electrolyte
AFC	$H_2 + 2(OH)^- \rightarrow 2H_2O + 2e^-$	$1/2\,O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$	$H_2 + 1/2\,O_2 \rightarrow H_2O$
PEMFC	$H_2 \rightarrow 2H^+ + 2e^-$	$1/2\,O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$H_2 + 1/2\,O_2 \rightarrow H_2O$
PAFC	$H_2 \rightarrow 2H^+ + 2e^-$	$1/2\,O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$H_2 + 1/2\,O_2 \rightarrow H_2O$
MCFC	$H_2 + CO_3^{2-} \rightarrow 2H_2O + CO_2 + 2e^-$	$1/2\,O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$	$H_2 + 1/2\,O_2 + CO_2 \rightarrow H_2O + CO_2$
SOFC	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	$1/2\,O_2 + 2e^- \rightarrow O^{2-}$	$H_2 + 1/2\,O_2 \rightarrow H_2O$

Source: Vision Engineer (website)

3.3 Fuel for Fuel Cells

Hydrogen, the fuel of fuel cells, does not exist in nature in its pure form. It has to be separated from chemical compounds, by electrolyses from water or by chemical processes from hydrocarbons or other hydrogen carriers, such as natural gas, methanol, gasoline, diesel, or gasified coal.

The main function of the fuel cell system is generating electricity. Meanwhile, significant amounts of heat are generated too by some fuel cell systems, especially those that operate at high temperatures such as solid oxide and molten carbonate systems. This excess energy can be used to produce steam or hot water or can be converted to electricity via a gas turbine or other technologies. This increases the overall energy efficiency of the systems. The efficiency of a power and heat cogeneration fuel cell can reach more than 30% for power outputs up to 30kW and 50% for power outputs up to 100kW. Fig. 3.4 shows a simplified flow chart of a fuel cell system.

A reformer is typically used to convert hydrocarbons into a gaseous mixture of hydrogen and carbon compounds called "reformate". In many cases, the reformate is then sent to another reactor to remove impurities, such as carbon oxides or sulfur, before it is sent to the fuel cell stack. This prevents impurities in the gas from binding with the fuel cell catalysts. This binding process is also called "poisoning", since it reduces the efficiency and life expectancy of the fuel cell. The total process, including reforming and cleaning of the fuel, is denoted "fuel processing". Figure 3.5 shows the different fuel processing for each fuel cell type. It is clear that the fuel processing becomes more and more complex with decreasing fuel cell temperature and efficiency.

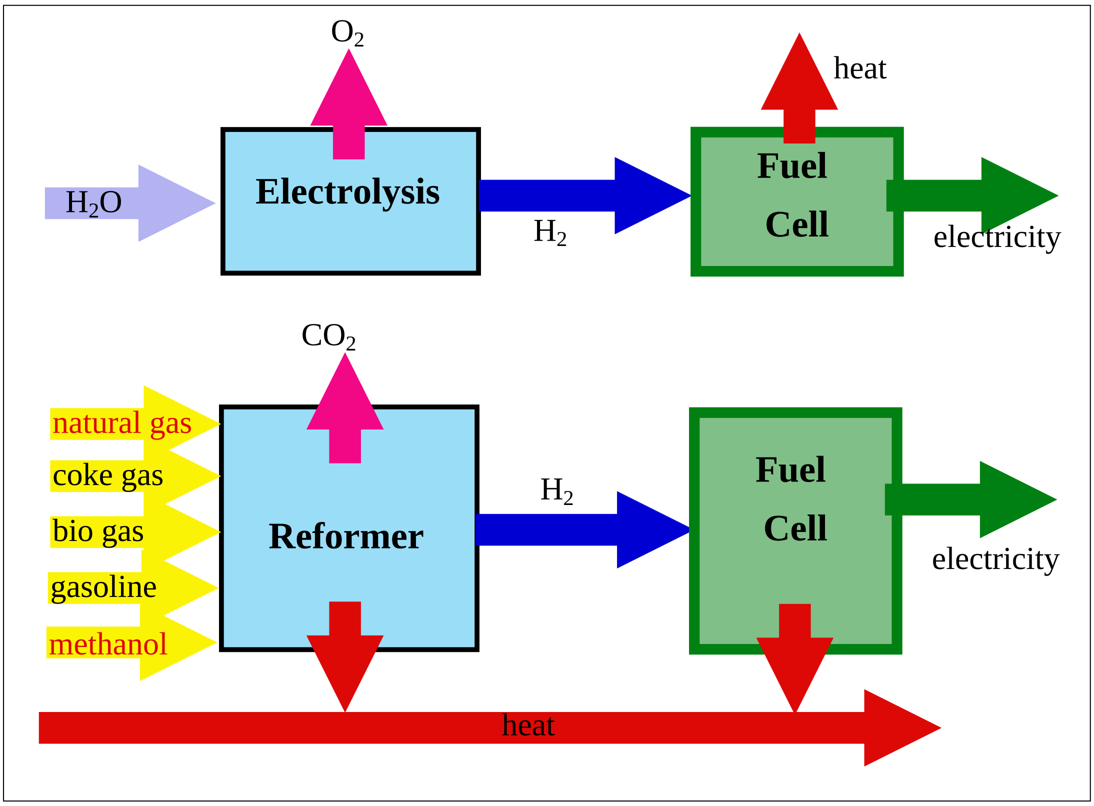
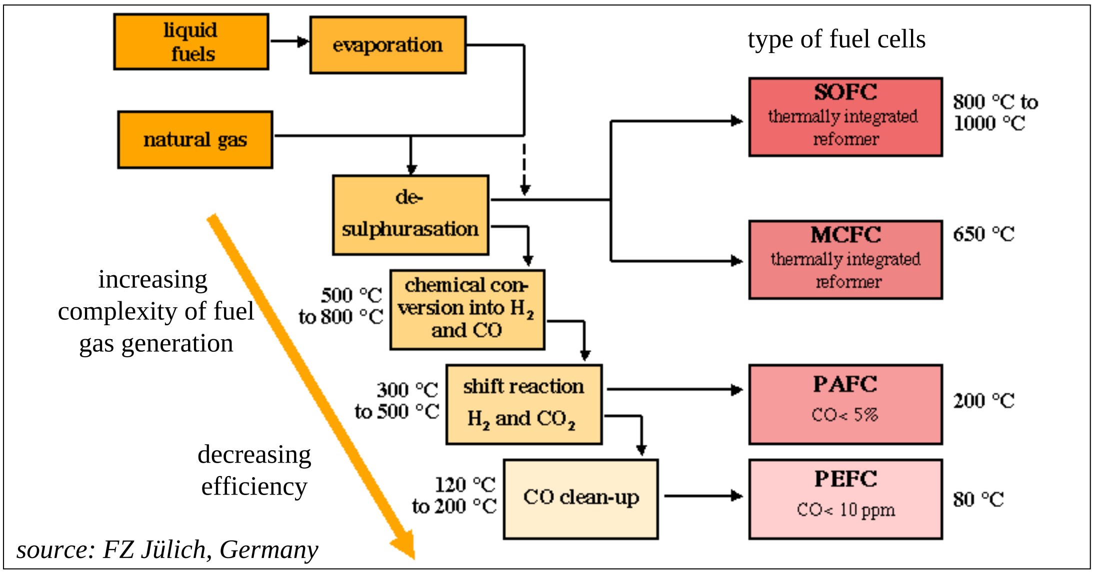


Figure 3.4: Simplified Flowchart of a Fuel Cell System



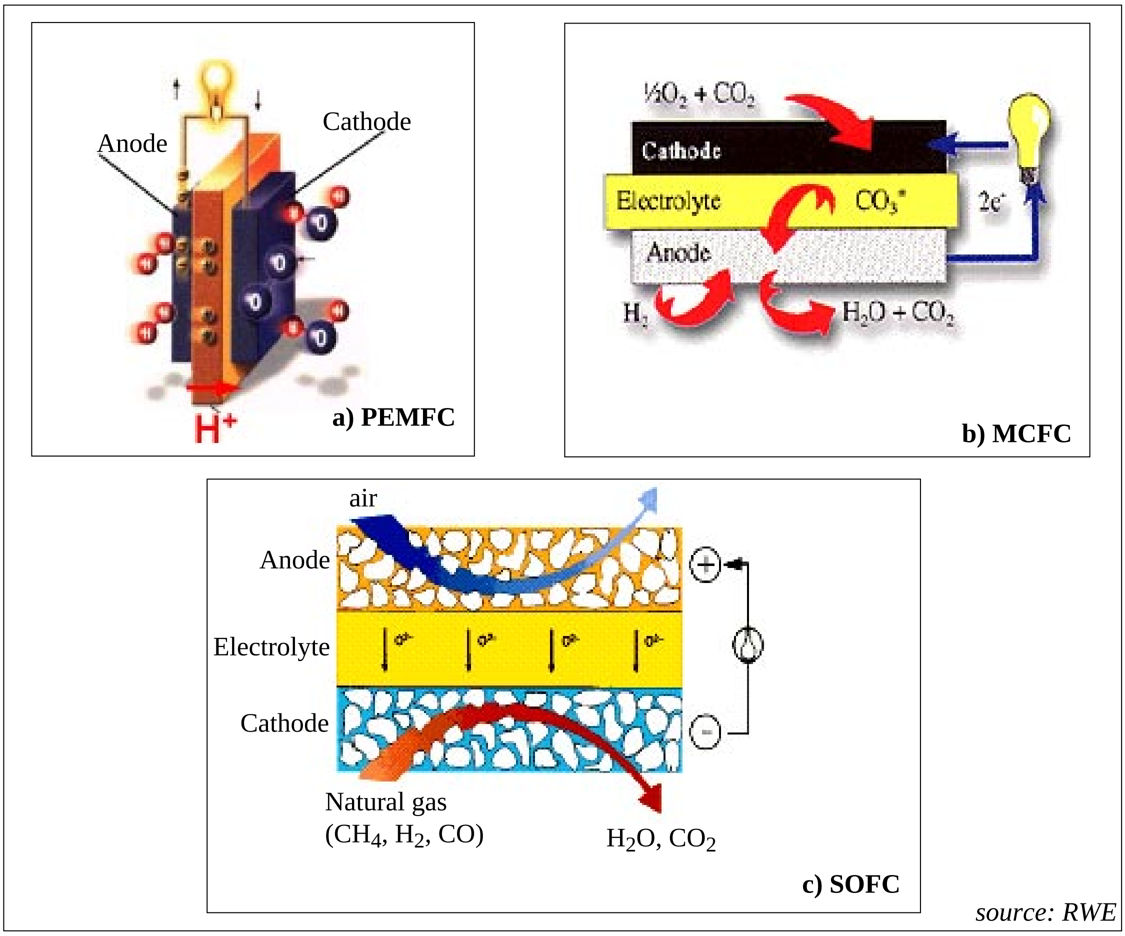
source: FZ Jülich, Germany

Figure 3.5: Fuel Processing of Different Fuel Cell Types

Reformers can be divided into external reformers and internal reformers. External reformers include three types: steam–methane reformers, partial oxidation reformers and auto-thermal reformers. They differ with regard to the chemical processes used, efficiencies and capital costs. Steam methane reforming is the most mature of these technologies, having been used for commercial hydrogen production for many years, but other reformer technologies are also being developed. Internal reforming occurs in the higher temperature SOFC and MCFC types, and is the process whereby methane is reformed directly into a $H_2/CO/CO_2$ gas mixture due to the high temperatures /20/. These fuel cell types thus do not need the complicated external reformer, and this is an advantage from the perspective of capital costs and system complexity.

3.4 Structure of Fuel Cells

A fuel cell is identified by its electrolyte, as was mentioned above. It has emerged as a viable system, which is shown in Fig. 3.6.



a) PEMFC

b) MCFC

c) SOFC

source: RWE

Figure 3.6: Different Structure of Fuel Cells

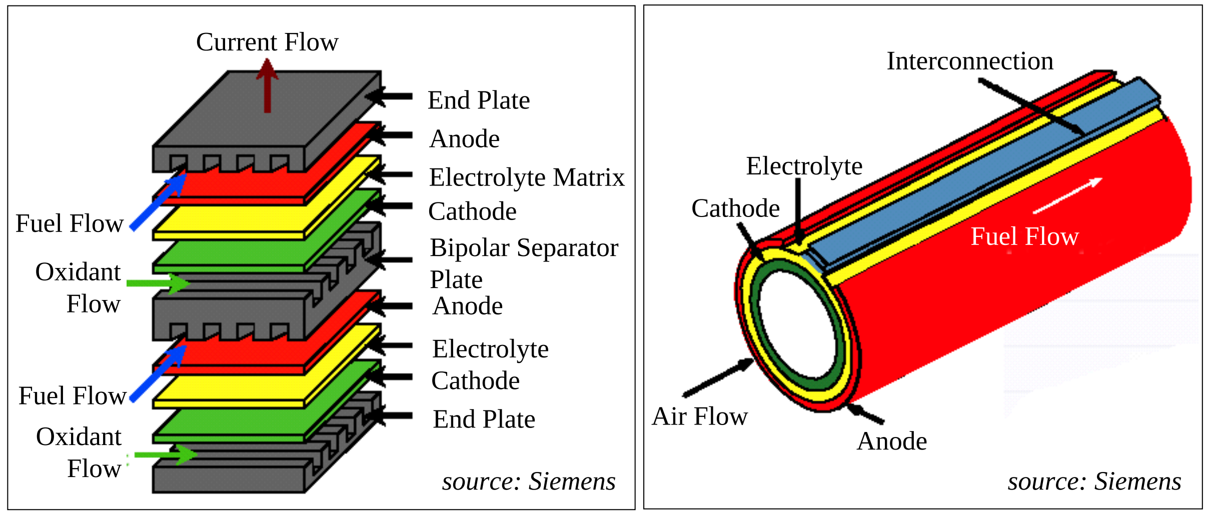
The electrolyte can be acidic (PEM, PAFC, DMFC) or alkaline (MCFC, AFC). Electrolyte

Membranes (PEMFC) serve as fixed acidic electrolyte. It is a solid ion exchange membrane used to condent protons. Hardware corrosion and gas crossover are minimized as a result of the solid electrolyte and very high current densities as well as fast start-up times have been realized for this cell.

In the MCFC, the electrolyte usually consists of a combination of alkali carbonates retained in a ceramic matrix. At the high operating temperature the alkali carbonates form a highly conductive molten salt, with carbonate ions providing ionic conduction. A circulating liquid electrolyte can be used as a heat management, concentration-adjusting and water-balancing feature. Immobilization can be achieved by a micro porous matrix (Asbestos) as in space AFCs, or by crystallizing/gelling the electrolyte as in a PAFC.

A high temperature solid-state electrolyte is the ceramic material used in the SOFCs. The electrolyte always remains in a solid state, adding to the inherent simplicity of the fuel cell. The solid ceramic construction of the cell can minimize hardware corrosion, allows flexible design shapes, and is impervious to gas crossover from one electrode to the other. Unfortunately, the high operating temperature limits the materials selection, which results in a difficult fabrication process. In addition, the ceramic materials used for the electrolyte exhibit a relatively low conductivity, which lowers the performance of the fuel cell.

The basic geometries of fuel cells can be divided into planar and tubular cells. The most commonly used fuel cell geometry is the **planar cell**. In a planar cell, anode, electrolyte (membrane) and cathode are put together in a sandwich structure, which is shown in Fig. 3.7a.



a) Planar Cell **b) Tubular Cell**

Figure 3.7: Basic Geometries of Fuel Cells

To achieve higher output voltages and higher power, planar single cells are often combined to planar fuel cell stacks. In doing so, multiple single cells are stacked together and form a planar fuel cell stack. The planar fuel cell stack is electrically a serial connection of a certain number of single fuel cells. Therefore, it is fairly easy to realize almost any output voltage requirement, as in a serial connection the single cell voltages add up. If you need a open circuit voltage of app. 17 V (translates to a nominal voltage of app. 12 V, since the MPP of a single cell is around 0.7 V), for example, 17 single cells need to be connected in series to form a stack with the desired output voltage. In theory, planar stacks could consist of hundreds of single cells, but in real applications there are limits due to thermal management (heat removal), gas flow (hydrogen and oxygen) and water management (PEM fuel cells).

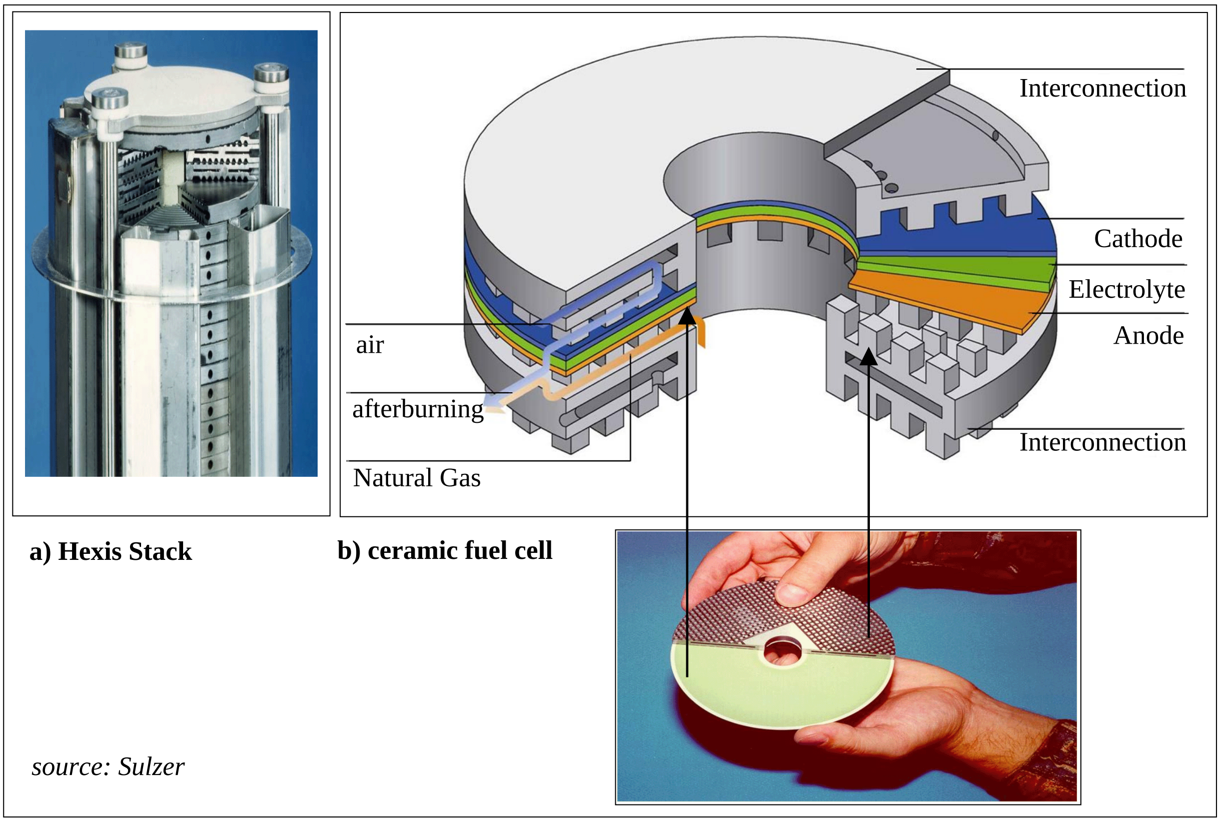
A second possibility to combine multiple single planar cells is the so called **stripe cell**. Here the single cells are not piled together but rather combined in a single level. This geometry is used when very flat geometries are needed (for example fuel cell to be integrated in laptop screen).

One problem with the planar cell is leakage, which decreases the efficiency and output of the fuel cell. Leakage exists not only in the sandwich structure, i.e. around the electrolyte, but also at the connectivities of the fuel cells. Another problem exists in the fuel supply, especially for larger units. It is not easy to keep a uniform fuel supply to each single fuel cell and thus obtain a uniform output for each fuel cell.

With the **tubular cell** the anode, electrolyte and cathode form a tube, as shown in Fig. 3.7b. The inner side of the tube is normally the anode layer (hydrogen side) which is covered by the electrolyte layer followed by the cathode layer (oxygen side). As with the planar cells it is possible to connect multiple single tubular cells in series to form a array of tubular cells. Nowadays tubular cells are utilized in the Siemens-Westinghouse SOFC. A tubular cell has a better performance where leakage is concerned than the planer cell. It is also somewhat easier to control a uniform fuel supply in the tubular cells. Therefore tubular cells are currently considered to be a more promising cell geometry for the developing technology.

Sulzer Hexis develops fuel cells for residential application based on the Solid Oxide Fuel Cell (SOFC) with a temperature of about 900°C. The heart of the Sulzer Hexis fuel cell is a electrolyte of zirconium oxide ceramic with electrodes (anode and cathode), which is illustrated in Fig 3.8.

Apart from the fuel cell, a Hexis stack segment consists of metallic interconnections or current collectors. A stack is comprised of 50 of these segments. The current collectors are responsible for gas distribution, heat exchange and establishing electrical contact between the individual segments. The fuel gas enters the channels of the current collector from the inside and it flows through them in a radial direction, passing over the anode. The atmospheric oxygen is fed from the outside, heats up inside the current collector and is diverted back over the cathode.



a) Hexis Stack

b) ceramic fuel cell

source: Sulzer

Figure 3.8: Illustration of Sulzer Hexis Ceramic Fuel Cell and its Structure

3.5 Applications of Fuel Cells

Fuel cells operate much like a common battery, but produce electricity through consumption of an external fuel rather than through consumption of the internal electrodes. The electrical output of the fuel cell can be altered by appropriately engineering the size and number of stacks within the cell. Furthermore, the overall efficiency of fuel cells is independent of their size. As a result, fuel cells can be scaled to produce a very wide range of products suitable for many applications. In fact, fuel cells can be configured for any application requiring DC or AC electricity. Their application area can be mainly divided into four parts, which are summarized in the Tab. 3.3.

Applications for stationary fuel cells are numerous. The size of stationary fuel cells ranges from about 5 kW to 250 kW and up. Stationary fuel cells are a product in themselves. Therefore, these fuel cells can be marketed on their own merits. In addition, the ready availability of fuel options such as natural gas and propane will help to overcome any limitations in the hydrogen supply infrastructure. Stationary applications appear most promising for the near-term commercialization of this technology. It can be combined with other power generating technologies, such as gas turbines, to create hybrid systems, which increase the overall system efficiency.

Applications for portable fuel cells include small (1-50 kW) units used to power wheel chairs, golf carts, lawn mowers and so on. For many of these applications, fuel cells could replace battery storage with potential improvements in weight and time between recharging.

Table 3.3 Fuel Cell Market Segments

Market Segment	Power Rating	Example applications
Stationary	5-250+kW	Residential and commercial power units, grid connected power, distributed generation, combined heat and power (CHP), premium power, uninterruptible power supply (UPS). remote power, back-up power
Portable	1-50 kW	Wheel chairs, golf carts, truck and rail refrigeration units, road signs, space vehicles and satellites
Mobile	25-150 kW	Cars, buses, other vehicles, naval and submarine vessels
Micro	1-500 W	Cell phones, PDA's, notebook computers, military hardware, portable electronics

source: Fuel Cells Texas, Inc.

Different application areas have different requirements for the fuel cells. For the stationary application, for example, the fuel cell should be available over 10 years with a required power production time between 40,000 to 80,000 hours. The specific target cost should be about 1500 US$/kW. For transportation applications, the fuel cell should be available approximately 10 hours while the required power production time is about 5000 hours. The requirement on the fuel cells are summarized in the Tab. 3.4.

Fuel cell power stations have achieved some success in practical applications. A 100 kW SOFC cogeneration system supplied by Siemens-Westinghouse first operated in the Netherlands. The system has a power limit of approximately 140 kW, normally feeding 109 kW into the local grid and 64 kW of heating energy for hot water into the local district heating system. It operates at an electrical efficiency of 46% with no performance degradation to date. As of January 2002, the system has operated for a total of 20,000+ hours. For another project four 200 kW UTC fuel cells were installed in the First National Bank of Omaha and now serve as the bank's primary power source. Heat from the fuel cell installation also provides energy for space heating, increasing the overall efficiency of the fuel cell system to more than 80%. Austin Energy is installing a 200 kW fuel cell at the RBJ Health Clinic building in downtown Austin. The power plant will be fueled by natural gas with an on-board hydrogen reform.

3.6 Costs of Fuel Cells

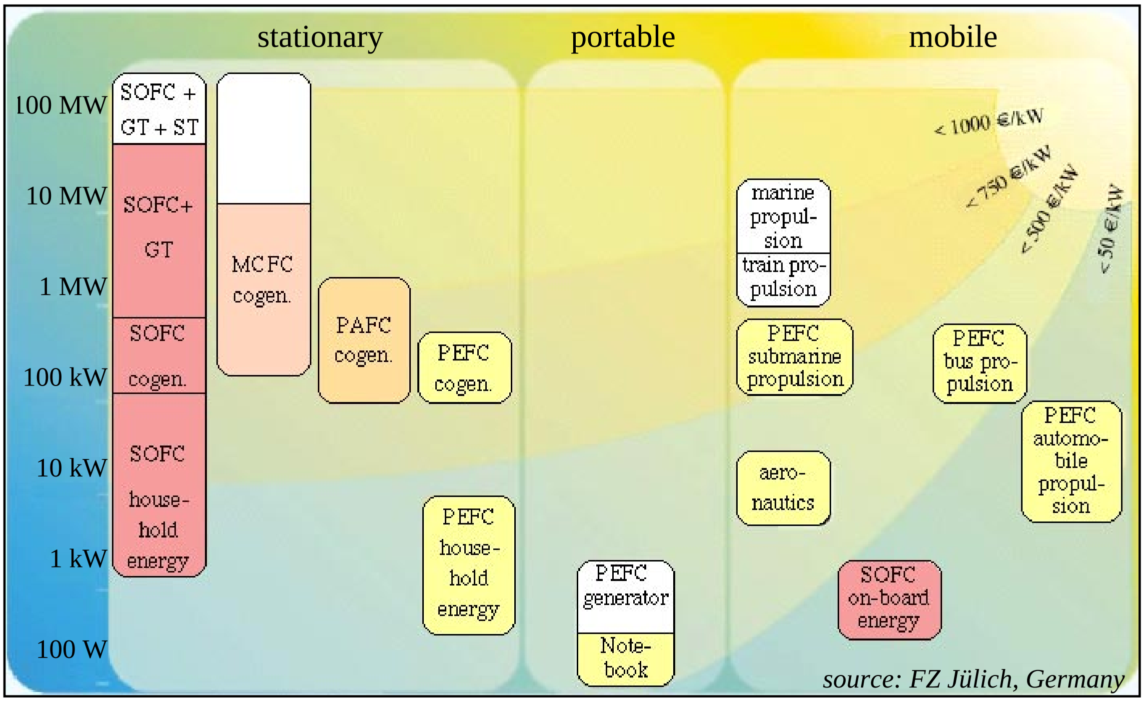
The high costs for building fuel cells are one of the largest impediments to the commercialization of fuel cells. Lowering production cost is critical to being able to use the technology in real-world applications such as hand-held electronics, vehicles and as a power supplier. Figure 3.9 illustrates the cost of the fuel cell in different application areas. In the

Table 3.4: Requirements for Fuel Cells in Different Applications

	stationary	**transportation propulsion**	**transportation auxiliary power**	**portable**
total life time	>10 years	about 10 years	about 10 years	1 -5 years
required power production time	40,000-80,000 hrs	5000 hrs	5000 hrs	1000-5000 hrs
thermal cycle	100	5000	>10,000	depending on application
system Efficiency	>50%	>40%	30 -40%	>20%
unit size	• 100-1000 kW decentralized power • 1-50 kW residential power	• 50-70 kW automobiles • 500-5000 kW trams-trains • 5-500 kW boats • 1000-20,000 kW ships	• 5-10 kW automobiles,trucks, boats • 50-200 kW airplanes • 100-1000 kW ships	• 0.1-5 kW
specific target	limited through materials' cost	1 kg/kW	10 kg/kW automobiles <<5 kg/kW airplanes	limited through portability
specific target cost	1500 US$/kW	30-50 US$/kW automobiles	100-200 US$/kW automobiles	<5000 US$/kW
allowable degradation rate*	0.13-0.25 %/1000 hrs	2 %/1000 hrs	2 %/1000 hrs	2-10 %/1000 hrs

source: FZ Jülich, Germany

stationary application area, SOFC and MCFC are the most likely fuel cell types for distributed power supply (output >10kw). The corresponding costs should be lower than 1000 Euro/kW. For residential application energy, the costs must be lower than 500 Euro/kW. Such costs are extremely higher than that of current power supply technologies. However, technological improvements may be drive down the costs enough to allow fuel cells to be a viable alternative.



source: FZ Jülich, Germany

Figure 3.9: Illustration of Fuel Cell Cost in Different Application Area

For the users, the most interesting question is may be "How much money can I save if I use FC power system for electricity and heating?". Basically, it should be a function of the fuel cell's efficiency and availability. Figure 3.10 and Figure 3.11 show the relationships between saved costs versus efficiency and availability, which are calculated based on an Fuel Cell Operating Cost Calculator. Based on a field test implemented by the department of defense (DoD), it is said that a PEMFC can reach an efficiency of about 22% and an availability of 90%. Therefore, 32,000 Euro per year can be saved in this case. In the field test, the PAFC has an efficiency about 32% and an availability about 66%. It is estimated that, using a PEMFC, one can save about 45,000 Euro per year.

It should be noticed that although a PEMFC has a 90% availability, it only works for 1 month. It means such a fuel cell is not practical to be used for a car or as a residential power supplier. Therefore, the criteria for choosing fuel cell should include efficiency, availability as well as the function period.

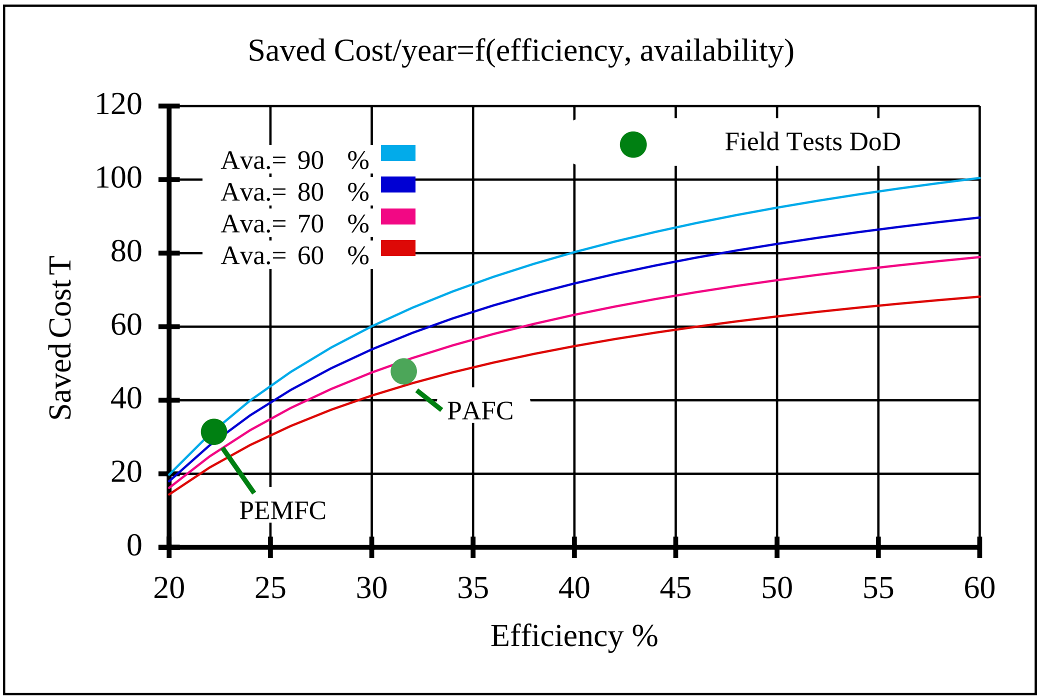


Figure 3.10 Relationship Between Saved Cost and Fuel Cell Efficiency

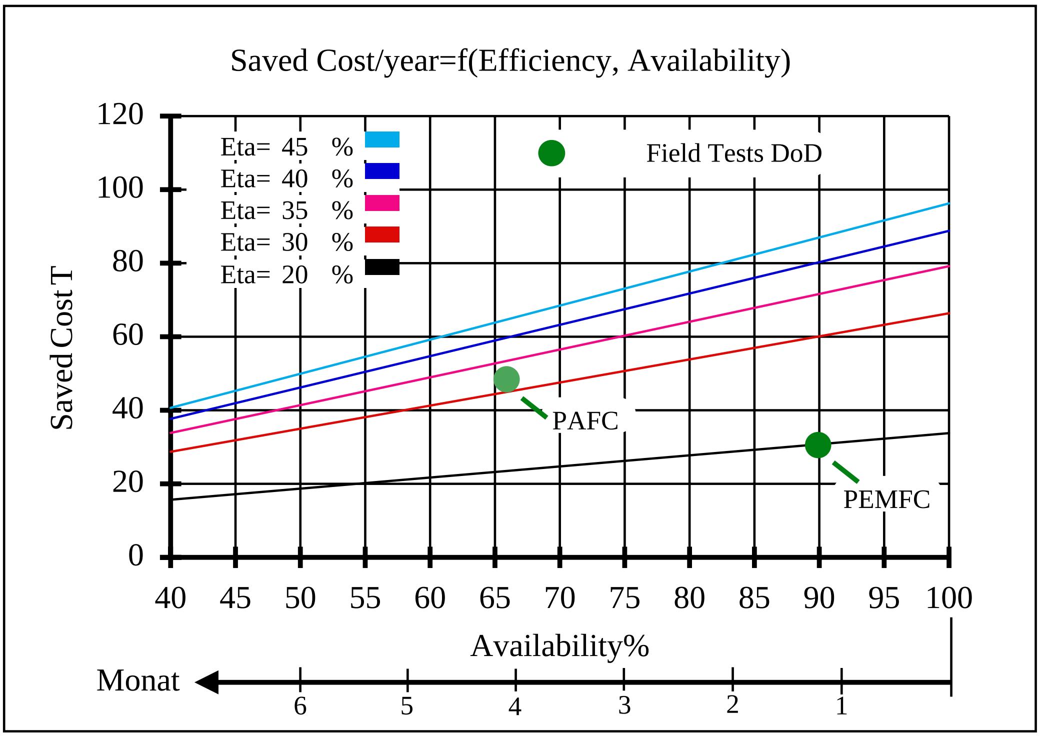
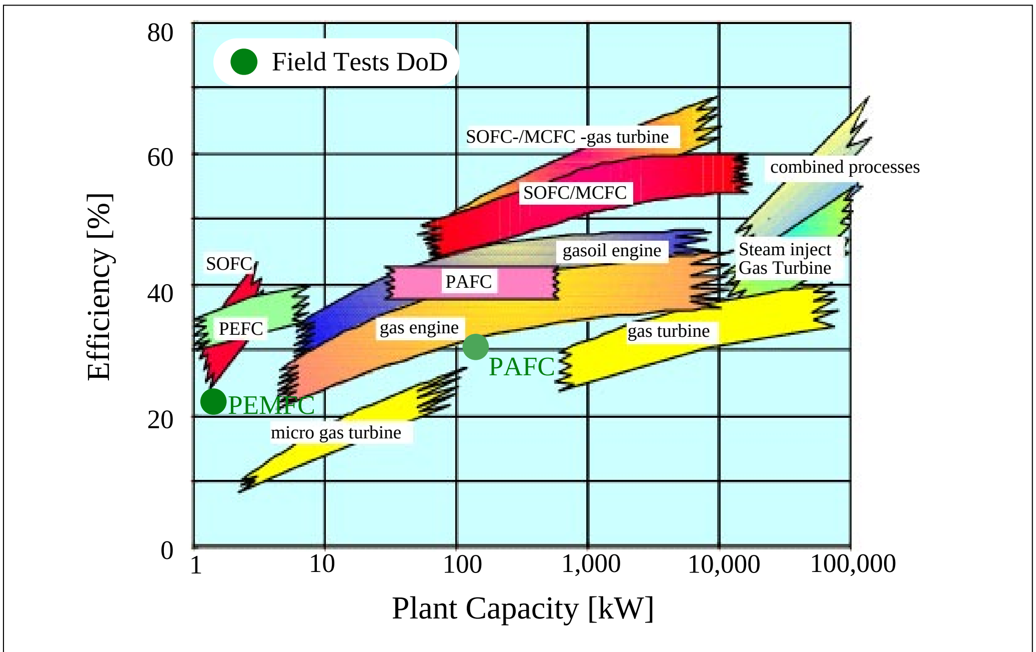


Figure 3.11 Relationship Between Saved Cost and Availability Period of Fuel Cell

4. HYBRID MGT/FC SYSTEM

4.1 Basic Concept of Hybrid System

Studies on plant concepts for SOFC/GT-systems attracts more attentions recently /1, 21, 22, 23/. A hybrid system consisting of a micro turbine and a SOFC achieves electrical efficiencies that are comparable to those of large power plants and beyond, especially in the case of direct integration and high SOFC-operating temperatures and turbine inlet temperatures, as shown in Fig. 4.1 and Fig. 4.2.

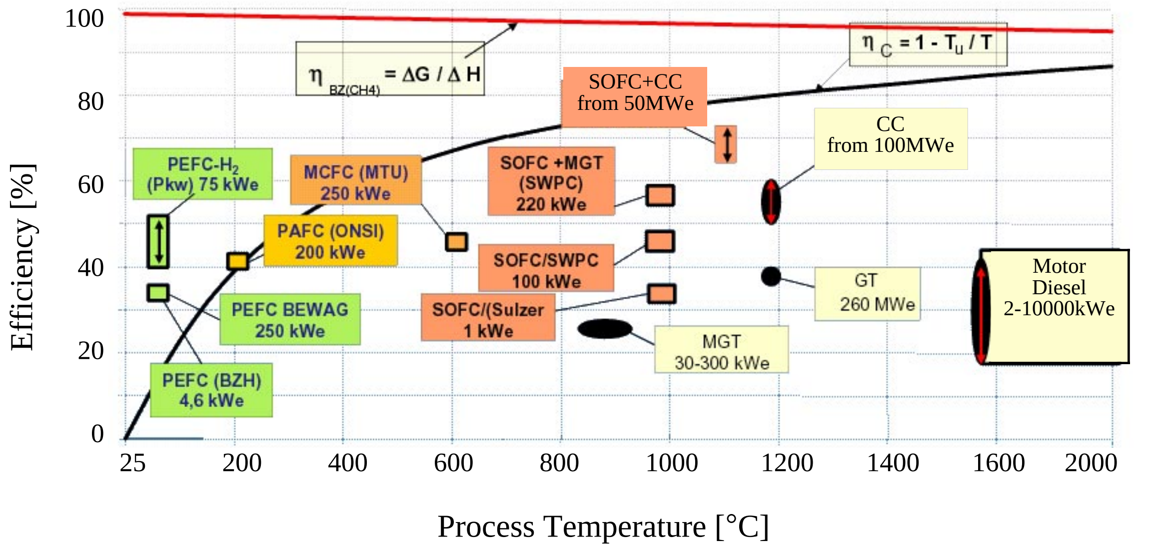


Source: Birnbaum, K.U. Monograph on Fuel Cells for Stationary Application

Figure 4.1: Relation Between Plant Capacity and Electric Efficiency

A MGT has a smaller volume and weight but also a lower efficiency (about 30%) and larger emissions than a "normal" gas turbine. Therefore, a MGT working as a stand-alone device generates not so much benefit. A fuel cell is a clean energy generator and has a considerably higher and constant efficiency even at different operating temperatures, but its volume is still extremely large. The comparison between a MGT, an engine and a hybrid system can be seen in Tab. 4.1.

Normally, the fuel cell is a SOFC (solid oxide fuel cell) which works at temperatures of about 950°C, so that the temperature level of the exhaust heat is high enough to be used for the operation of a micro turbine. At the same time the exhaust heat of the turbine can be utilized in the fuel cell for the preheating of cathode- and anode-gas. The fuel utilization of solid oxide fuel cells lies in the range of 80% to 85%. Therefore, a further enhancement of the efficiency is possible by an additional combustion of the fuel cell exhaust in the combustion chamber of the turbine. This means that hybrid MGT/FC systems could be a promising technology for distributed power supply. More research needs to be done in order for the FC to increase the specific output and decrease its volume. It is expected that hybrid MGT/FC systems can reach an efficiency of up to 75% based on further technological improvements.



Source: Forschungszentrum Jülich - IWV3

Figure 4.2: Relation Between Process Temperature and Electric Efficiency

Table 4.1 Comparison among MGT, Motor and Fuel Cell

Type	Efficiency	Volume and weight	Emission
MGT	30%	Small	Large
Motor	35-38%	Medium	Medium
FC	50% ±5%	Large	No additional emission

It should be mentioned that the estimated efficiency of PEFCs and PAFCs are both somewhat higher than the field test results from the DoD, which are marked as green dots in Fig. 4.1.

4.2 Application of Hybrid System

Hybrid system can be applied in the residential area as well as in small industry, trade and services or public buildings as they offer an opportunity for an environmentally friendly electricity supply and, at the same time, a cooling and heat supply with a high fuel utilization.

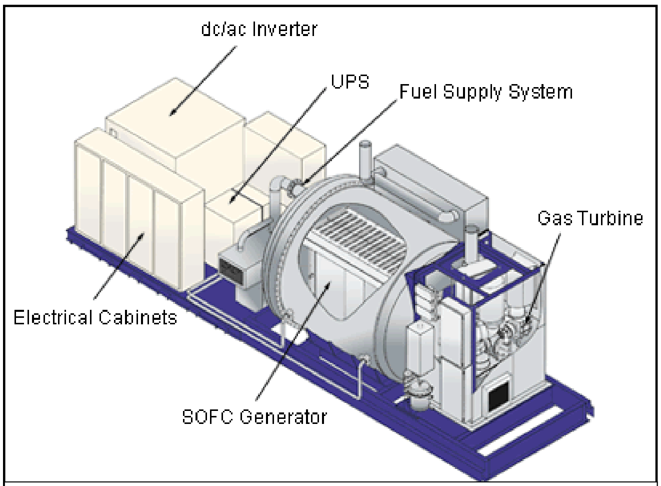
The world's first SOFC/gas turbine hybrid system was delivered to Southern California Edison for operation at the University of California, Irvine's National Fuel Cell Research Center. The hybrid system includes a pressurized SOFC module integrated with a micro turbine/generator supplied by Ingersoll-Rand Energy Systems (formerly Northern Research and Engineering Corp.), as shown in Fig. 4.3. The system has a total output of 220 kW, with

200 kW from the SOFC and 20 from the micro turbine generator. This system, a photograph of which is shown below, is the first-ever demonstration of the SOFC/gas turbine hybrid concept. This proof of concept demonstration is expected to demonstrate an electrical efficiency of ~55%. The system is being tested at the NFCRC to determine its operating characteristics and operating parameters. As of January 2002 the system has operated for 900+ hours and has demonstrated 53% electrical efficiency. It will be operated for several more months to gain experience for the design of prototypes and commercial products. Eventually, such SOFC/GT hybrids should be capable of electrical efficiencies of 60-70%.

a) 220 kW hybrid SOFC/MGT system demonstrated at California

Efficiency: 53%

Output: 220 kW



System Illustration of the 220 kW hybrid SOFC/MGT System

Source: Siemens and Westinghouse

Figure 4.3:World's First Hybrid SOFC/MGT System

4.3 Integration of the Hybrid System

4.3.1 Integration of MGT and SOFC via Heat Exchanger

The simplest fuel cell/gas turbine cycle consists of a coupling of the two components by a heat exchanger. In this case the fuel cell exhaust heats compressed air in the micro gas turbine recuperator (Fig. 4.4) while anode and cathode gas preheating is done with heat from the gas turbine exhaust gas and the heat released from combustion of residual fuel contained in the fuel cell exhaust gas. As this concept leads to high temperatures at the recuperator exit, there is only small additional firing necessary to reach the nominal turbine inlet temperature, provided this is in the same range as the temperature of operation of the fuel cell. The high temperatures that occur in the recuperator require special materials, however, particularly high temperature alloys or expensive ceramics /6/. There is still the need to develop inexpensive and heat-resistant materials, resulting in components with a sufficient life-span. The same problem occurs at the interconnection between SOFC and recuperator. An additional problem in this area is the necessity for adapting the cooling system of the combustion chamber walls to the elevated temperatures of the entering gas. Often the combustion chamber is kept in operation after the introduction of the fuel cell exhaust gas into the process. This is done in order to reach the maximum turbine inlet temperature. But then the film cooling of the combustion chamber walls has to be modified in such a way that the admissible material temperatures are met. Otherwise, also in this area new materials have to be applied. Another possibility is to omit additional combustion and to accept lower turbine inlet temperatures.

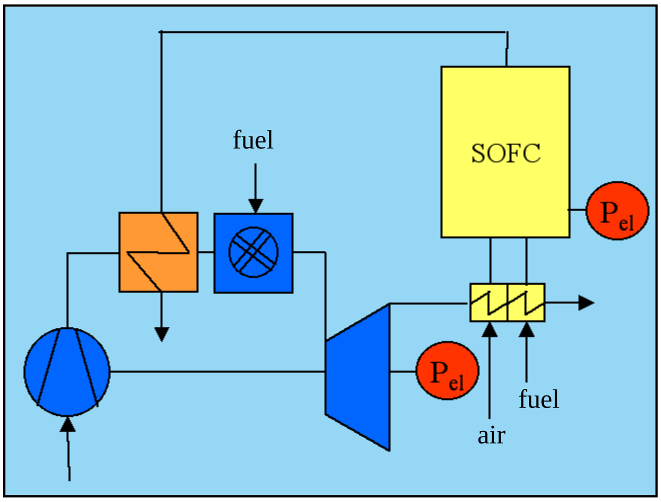


Figure 4.4:Integration of a Micro Turbine and a SOFC by a Heat Exchanger

With a recuperative combination of an SOFC and a micro gas turbine an electrical efficiency of 53% is obtained, if an SOFC temperature of 950°C at a turbine inlet temperature of 920°C and a pressure ratio of 6,5 are assumed. An increase in the gas turbine inlet temperature by additional firing in the combustion chamber of the gas turbine leads to a loss in efficiency as part of the fuel is only utilized in the gas turbine. If the allowable turbine inlet temperature is below 920°C, the exhaust heat of the fuel cell is only partially utilized and the efficiency will decrease. This leads to the optimum of efficiency at 920 °C. An increase in the SOFC temperature causes a moderate augmentation of the electrical efficiency; due to the higher operation temperature the air surplus at the cathode of the fuel cell decreases.

If future development of materials technology for micro turbines with turbine inlet temperatures of 1500°C is assumed, this will lead to system efficiencies as represented in Fig. 4.5. The graphs demonstrate that the high electrical efficiencies of SOFC/MGT-systems integrated via heat exchangers require increased SOFC-operating temperatures whereas higher turbine inlet temperatures obtained from additional firing reduce efficiency of this plant concept over the entire investigated range. Pressure optima of systems without additional firing are shifted to lower values compared to other studies conducted by e.g. Winkler & Lorenz, 2000 /24/. The reason for this is that additional losses due to higher pressure ratios - particularly on the micro gas turbine side - were taken into account here.

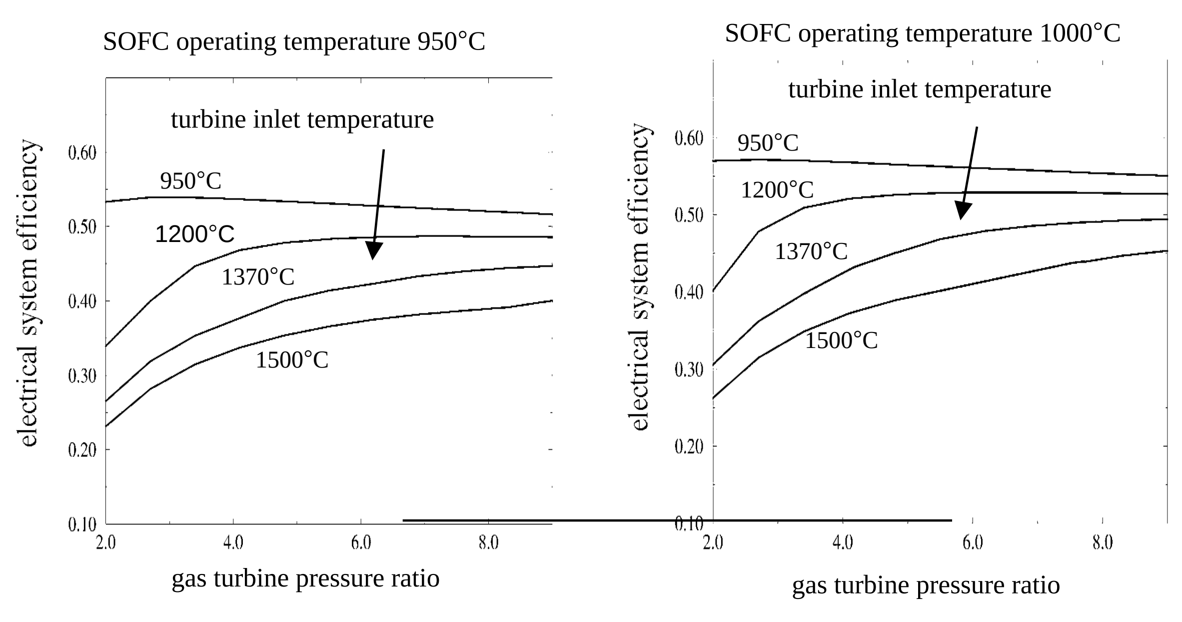


**Figure 4.5: Integration of SOFC and MGT by heat-exchanger:
Influence of gas turbine pressure ratio and turbine inlet temperature on efficiency
(SOFC-operating temperatures are 950°C and 1000°C) /25/**

When the SOFC and the MGT are coupled by a heat exchanger, power-to-heat ratios of up to 2.1 are realizable at a maximum SOFC-temperature of 950°C and at an exhaust temperature of 90°C at the stack. At SOFC operating temperatures and turbine inlet temperatures of 1000°C this coefficient increases to a value of 2.43 because of the enhanced electrical efficiency of the system. A large variety of power-to-heat ratios presupposes the possibility of separate operation of the fuel cell and the micro gas turbine, which is facilitated by bypass pipes and valves.

4.3.2 Direct Integration of MGT and SOFC

An alternative to combining a fuel cell and a micro gas turbine is the direct integration of the two components. If this is the case, the SOFC can be operated at higher pressure which is beneficial for its efficiency, and exegetic losses at heat exchangers are reduced. This configuration offers an electrical efficiency of 56.6%, assuming a conventional turbine inlet temperature and an SOFC operating temperature of 950°C. This result is in agreement with other studies based on state-of-the-art technology (e.g. Veyo et al., 2000 /1/). The plant concept for this configuration is shown in Fig. 4.6. The fuel cell exhaust gas still contains 15% to 20% of the original fuel as residual combustible substances. These can be utilized for further temperature augmentation before the hot gases are expanded in the micro gas turbine (see e.g. Pålsson, 2000 /26/), yielding a temperature gain of 160 Kelvin at reference point operation (T_{SOFC} = 950 °C, Π=6,5). This operating point represents the basic condition on which further parameter variations of design point operating parameters are based. Compared to the original concept, where residual fuel is burnt for additional internal cathode/anode gas preheating, this alternative design requires increased internal anode and cathode gas recirculation for temperature equalization.

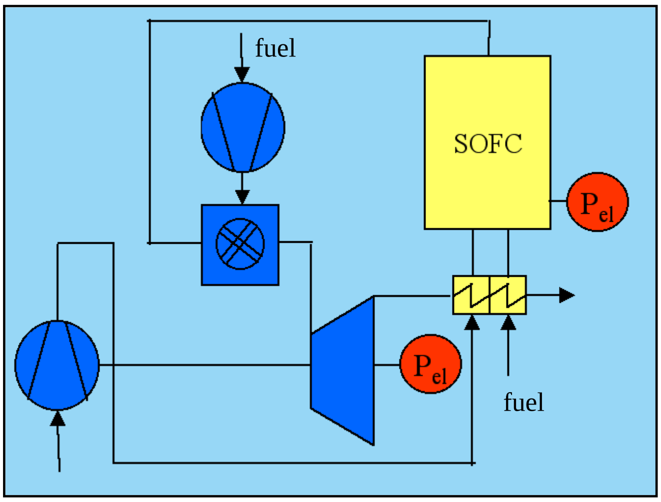
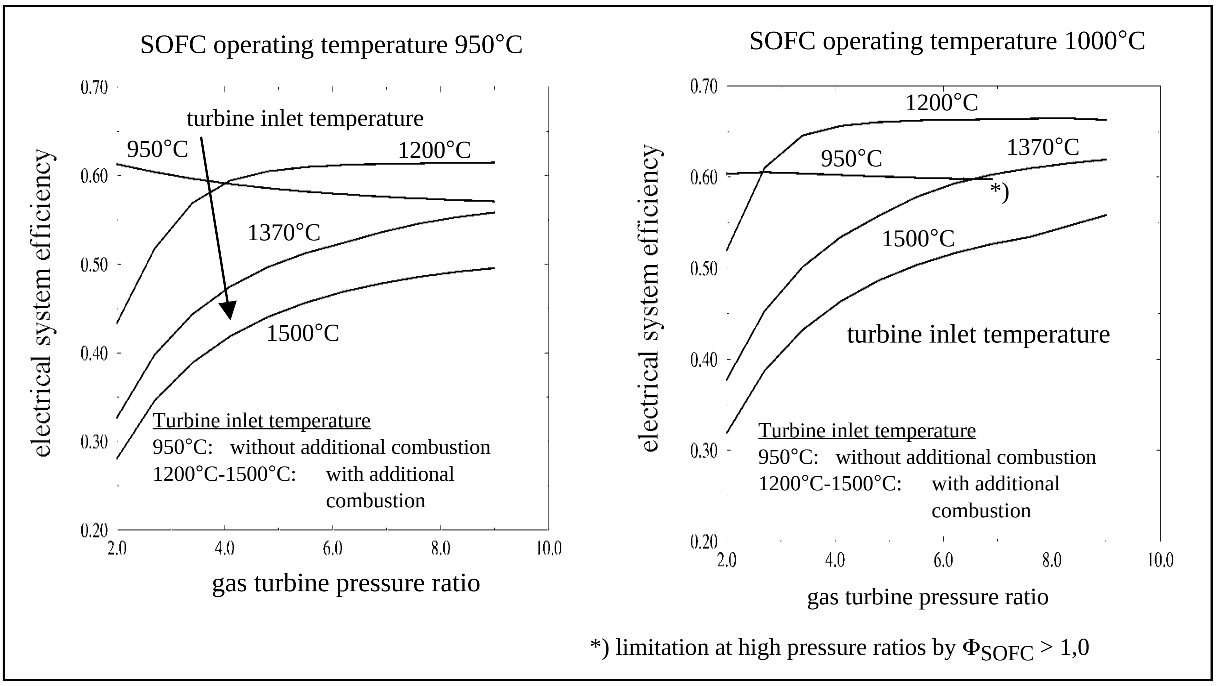


Figure 4.6: Direct Integration of a Micro Turbine and a SOFC



*) limitation at high pressure ratios by $\Phi_{SOFC} > 1,0$

**Figure 4.7: Direct Integration of SOFC and MGT by heat-exchanger:
Influence of gas turbine pressure ratio and turbine inlet temperature on efficiency
(SOFC-operating temperatures are 950°C and 1000°C) /25/**

Particularly at higher SOFC operating temperatures and intermediate to higher pressure ratios a significant increase of efficiency can be obtained compared to the original concept (Fig. 4.7). In the upper graph of Fig. 4.7, an optimum of efficiency of the system without ad-

ditional firing should be expected below the pressure range under investigation. For all scenarios assuming additional firing in the gas turbine combustor, efficiency increases with pressure. The reason for this behavior is that a larger portion of the fuel is added in the fuel cell rather than in the gas turbine combustor. This is reflected by an increase of temperature augmentation by residual fuel combustion compared to the above mentioned basic condition. It leads to a better fuel utilization at given turbine inlet temperatures.
The addition of conventional fuel should be limited to a minimum amount, in order to maximise the efficiency gain. This requires appropriate burner systems which avoid flash-back and ensure stable premixed combustion with a low amount of auxiliary fuel.

4.4 Efficiency Improvement of the Hybrid System

For small plants (taking into account that the plant should be as simple as possible), the highest efficiency potential is offered in the long run by a direct connection between a micro gas turbine and an SOFC with an internal methane reformation.
Figure 4.8 shows an efficiency potential of appr. 73% for the new technology. For a turbine inlet temperature of 1300 °C the optimum SOFC-temperature is 1060 °C and this corresponds to the current upper limit. In such a process, the energy of the fuel that is not converted in the SOFC will be utilized to increase the temperature of the hot gases entering the SOFC.

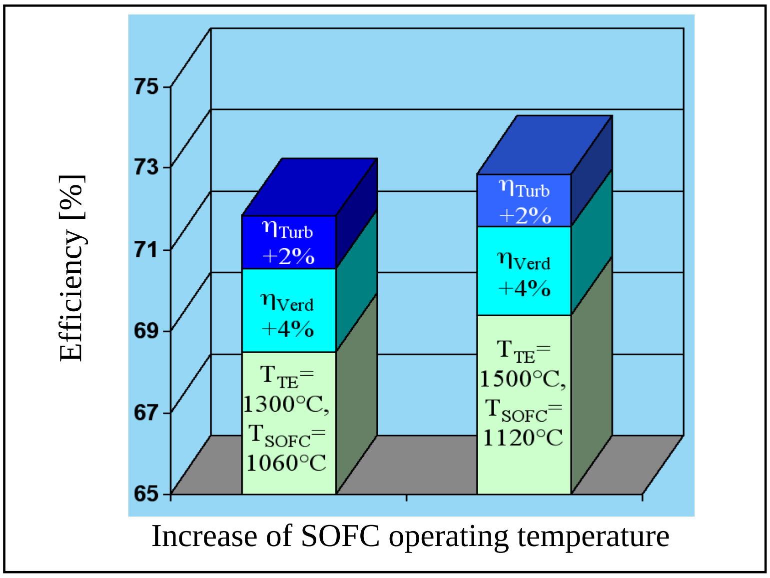


Figure 4.8: Influence of the Component Efficiency Improvement to the Total Efficiency Increase

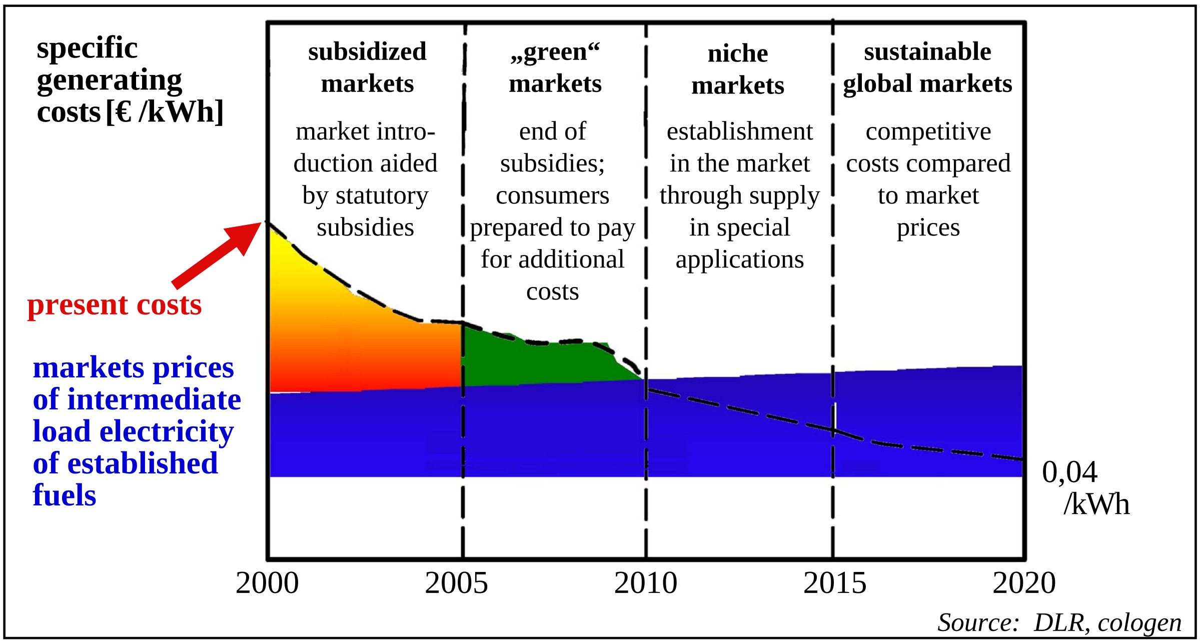
It is shown in Fig. 4.8 that for a turbine inlet temperature of 1500 °C the optimum SOFC-temperature lies at 1120 °C; this goes beyond the current state-of-the-art maximum material temperatures. Current development trends in the realm of SOFC fuel cells show no tendency towards higher temperatures, but on the contrary to a reduction of these temperatures. The reason behind this is that at the moment the primary aim is a quick reduction in investment costs. This means that the starting point for the shown efficiency potential is not given at the moment. It is therefore expected that the total efficiency for the direct integration hybrid system will reach 75% in the future.

5. ECONOMY OF THE NEW TECHNOLOGY

In order to be able to establish the new technologies against existing systems, it must be guaranteed that the future systems meet the economical demands. In the long run, new energy conversion systems can only be established on the market if cost-covering operation are possible.

The specific investment costs of a power plant based upon new technologies are higher when the power range of the facility is lower, as shown in Fig. 5.1. In addition to this, the specific investment costs of innovative concepts like as photovoltaics and fuel cell technologies increase drastically compared to conventional and well-engineered energy conversion systems like gas turbine technology or combustion engines.

In Fig. 5.2 possible steps for the introduction of a new technology in the existing energy market are illustrated /27/. In the first step, the high specific investment costs have to subsidized. Eventually, measures for cost reduction must be applied. This could be the utilization of alternative and cost-saving materials or the introduction of new production techniques to achieve higher quantities and, thus, a cost reduction by mass production. Operational reliability and availability must be considered very important issues as well.



Source: DLR, cologen

Figure 5.2: Steps towards the Introduction of new Technologies in existing Markets

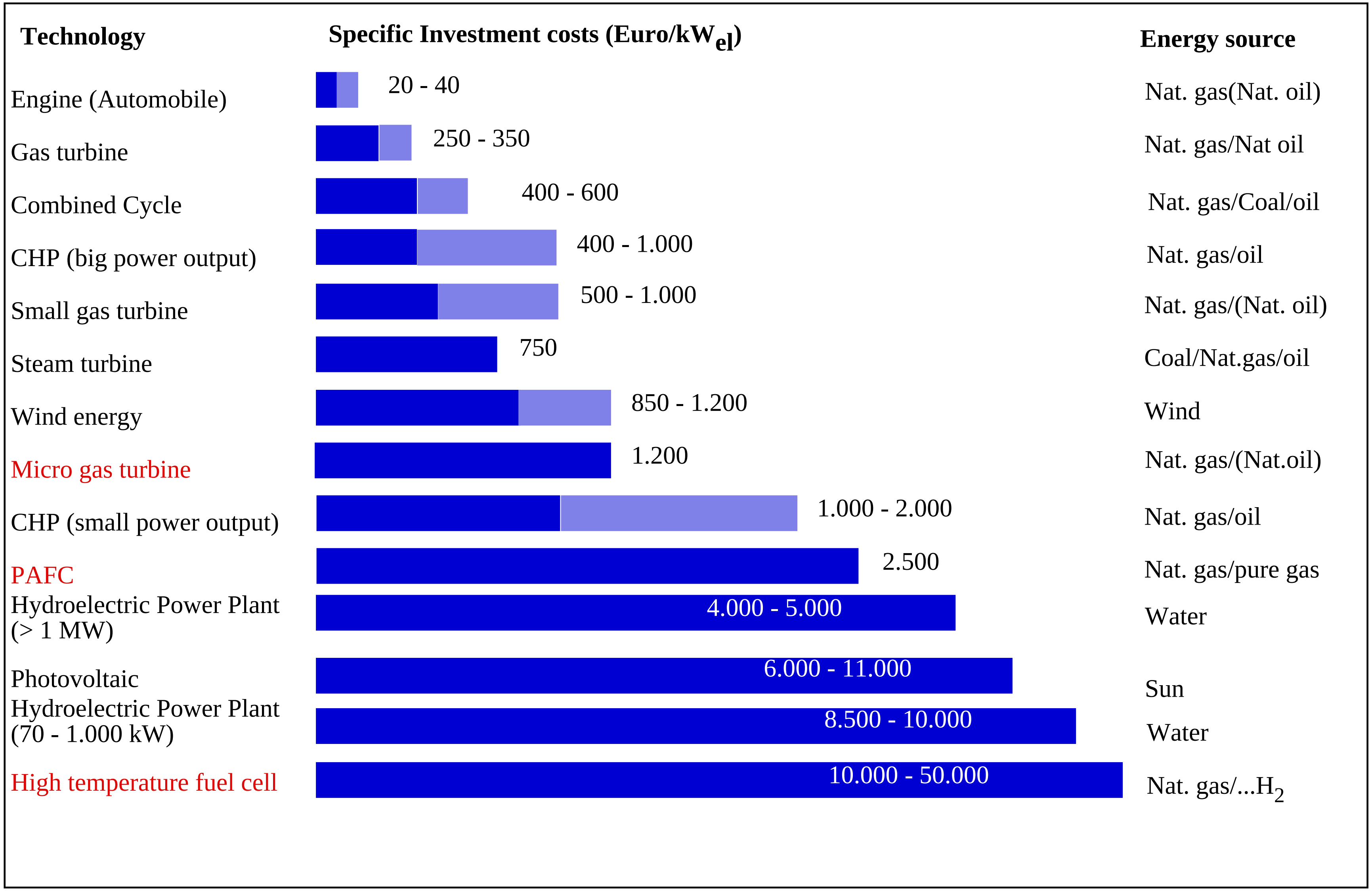


Figure 4.8: Specific Investment Costs and Typical Primary Energy Sources for Energy Conversion Technologies

6. CONCLUSION

Generating applicable energy generally demands the conversion of primary energy by application of different technologies. Electricity and heat are two of the most popular energy forms. The electricity market has traditionally been very centralized, but is transforming into a distributed market step by step, whereas the heat market is already decentralized. Due to the transformation of the electricity market small units providing both heat and power (CHP) like micro gas turbines and fuel cells will become more important. To be successful on the decentralized market, the new technologies must be highly flexible for varying electricity and heat supply with constantly high fuel utilization, reliability and security.

The hybrid system combining a micro gas turbine with a high temperature fuel cell (SOFC or MCFC) has proven it is one of the most promising systems for the decentralized energy market. Due to the high electrical efficiencies in the case of direct integration of the gas turbine and the fuel cell, system efficiency is expected to reach up to 75%. In order to achieve such an aim, the efficiency of micro gas turbines has to be improved by means of process optimization and the utilization of ceramic materials. Meanwhile, investment and the operation cost of fuel cells should be lowered to an acceptable level via technological breakthroughs.

At the moment the specific investment cost of the hybrid system are significantly higher than those of conventional systems. Due to its excellent performance and promising potential, however it can be expected that the hybrid systems can meet the economical demands in the future and realize cost covering operation.

7. ACKNOWLEDGEMENTS

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