

Article ID: 1000 8055(2007) 04-0565-12

Hybrid system- a promising way solving future energy problems

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Abstract: With the increasing demand for electricity, an efficiency improvement and thereby reduced CO₂ emissions of the power plants are expected in order to reach the goals set in the Kyoto protocol. In comparison to conventional systems, the hybrid systems with the use of synergetic effects offer the possibility to provide a substantial contribution to spare our natural resources and protect our environment.

Combined Cycle Power Plants belongs innately hybrid system in the centralized energy market. They can provide large amounts of power and have a quick start up time. The MGT/FC hybrid system is quite promising in the decentralized energy market. It is widely used in stand alone applications. Furthermore, the combination of fossil and renewable power plant technologies contains a large synergy potential to increase the efficiency of processes for power plants.

New materials, innovative cooling technology, new combustion concepts and optimized production methods are needed to make the potential of these new technologies accessible for a quantum leap in the efficiency. For this it needs considerable research work and good coordinated research projects between the state, industry, research laboratories and universities.

Key words: aerospace propulsion system; energy; hybrid system; turbine; fuel cell

CLC number: TK01; TK47; V231

Document code: A

Nomenclature

CHP	combined heat and power
EU	European Union
FC	fuel cell
MGT	micro gas turbine
PAFC	phosphoric acid fuel cell
PEFC	proton exchange fuel cell
SOFC	solid oxide fuel cell

Introduction

Energy is the source of general well being and provides the standard of living in every country. The energy production itself is faced with the increasingly stringent emission regulations to safeguard health and preserve the environment for future generations.

With the increasing requirement of electricity, an efficiency improvement and thereby re-

duced CO₂ emissions of the power plants are expected in order to reach the goals set in the Kyoto protocol. For Germany, the current predictions assume that 20% more electrical power will be generated in 2020 using about the same amount of fuel as now and that over 50% of the power will come from coal and lignite burning steam power plants. The only way to achieve this is to increase the efficiency. Therefore, new technologies and new concepts, in combination with an increase in the efficiency of systems for fossil primary energy carries as well as renewable energy, have to be developed.

These new power plant technologies and already used technologies should meet the criteria to cope with the requirement of generating electricity, heating and cooling in the future. Most

important requirement to such systems is the economical use of natural resources, which can be guaranteed by increasing the efficiency of the part processes or components in particular. The reduction of the CO₂ emissions is another target in energy conversion to improve the environmental compatibility of the technology used. At last the energy conversion technology must have sales opportunities on the world market to justify the enormous amount of money for new and further development^[1,2].

Hybrid systems currently are a promising way to meet the requirements of the future energy market. They are distinguished by the fact that two different technologies will be used in the same system for the same purpose. In the case of generating electricity, heating and/or cooling, two energy conversion technologies will be combined with each other. The sub processes in the hybrid systems are energetically coupled, instead of running separately. Therefore, taking advantage of synergy effects will be possible, a combined efficiency, which is higher than that of the sub processes, can be achieved.

Combined Cycle Power Plants are innately hybrid systems in the centralized energy market. The combined cycle power plant is a combination of the gas turbine and the steam turbine, adding together many of the advantages of the both. They can provide large amounts of power with their quick start up time. They have a short delivery time, a low heat rate, and the capital cost is an effective compromise between pure gas and steam turbine plants. In combination with an upstream gasification plant, combined cycle power plant technology can also be applied for non conventional fuels such as coal, petroleum coke or liquid refinery residues.

In the European Union (EU), it has been decided to deregulate the electric energy market. The different states of the European Union have to realize this decision and are in 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. Deregulating the electricity market leads to the necessity of smaller energy conversion units that can provide both electricity and heat to the customer. 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.

Hybrid systems containing a number of power generation devices such as wind turbines, photovoltaic, micro hydro and/or fossil fuel generators are generally independent of large centralized electric grids and are used in remote areas. These systems range from small systems designed for one or several homes to very large ones for remote island grids or large communities. They are seen as a way to provide power to the many remote communities in the developing world, where the costs for large scale expansion of electrical grids is prohibitive and the transportation costs of diesel fuel are also very high.

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. MGT/FC hybrid systems could be a promising energy provider in stand alone applications. A very high reliability of the energy conversion system is demanded.

The combination of fossil and renewable power plant technologies contains a large synergy potential to increase the efficiency of processes for power plants. Further investigations may focus on gas turbine and solar thermal plants, gas turbine and fuel cell plants, gas turbine and wind power plants, steam turbine and geothermal plants as well as steam turbine and solar thermal plants.

1 Combined cycle power plant process

The combined cycle power plant process be-

longs to the group of hybrid systems, as shown in Fig. 1. Such power plants could consist of gas turbines, which are coupled to steam turbines by a water-steam cycle. By using the waste heat of the gas turbine for the steam generator of the steam turbine process, a high synergetic effect is reached. Nowadays the highest efficiency of this energy conversion process on the base of natural gas in commercial use is 58%. The availability of such systems is clearly over 98%. Research work for development of new high temperature materials and cooling technologies in combination with new materials and structures can lead to a efficiency of 65 to 70% within the next 5 to 10 years^[3].

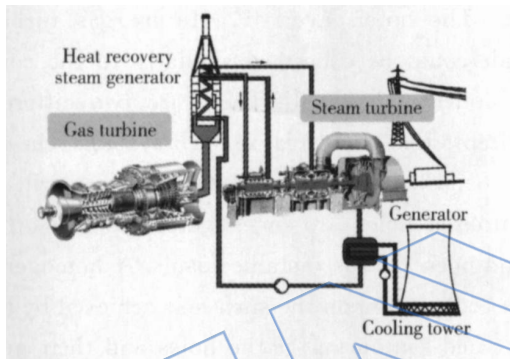


Fig. 1 Illustration of a combined cycle power plant process

By increasing the efficiency of power plants, not only that of the individual components, but also that of the interaction between the components, an important contribution to the preservation of natural fuel resources and reduction of emissions can be made. At present modern natural gas fired combined gas and steam turbine power plants can achieve total efficiencies of up to 58%. This implies turbine inlet temperatures (as defined in DIN ISO 4341) of approximately 1 230 °C in gas turbines and of a maximum of 600 °C in steam turbines. With these fluid temperatures one already reaches or even goes beyond the load limits of currently applied materials, which makes complex cooling technologies for the gas turbines, sophisticated constructions and revision manuals necessary, if one wants to guarantee a secure and long operating life.

The insight gained so far suggest that, com-

pared to the present state of the art turbines with ISO turbine inlet temperatures of 1 230 °C and live steam temperatures of 580~ 620 °C, the operating parameters of future plants such as temperature and pressure should be considerably increased.

To achieve a total efficiency of 65% it will be essential to realize gas turbines with combustion chamber outlet temperatures of 1 520 °C at a pressure of 17 bars. These high process parameters can be controlled by developing new materials, including thermal barrier coatings, in combination with improved cooling technologies. Improvements to one component only, as e. g. just the gas or steam turbine, will only achieve their full potential if these turbines are tuned to one another as far as their process parameters are concerned. The possibilities of increasing the operating fluid temperatures by solely developing the structural materials are limited both with 9% ~ 12% Cr steels and with single crystal nickel alloys^[46].

Because of this the foundations for the innovative design of the thermally and mechanically highly loaded components for optimized process control have to be laid by the combined interdisciplinary research of experts in fluid dynamics, structural mechanics, materials sciences and production engineering.

This means for the gas turbine the realization of more effective cooling technologies that also use less cooling fluid as, e. g., effusion cooling for the combustion chamber and the blading. Effusion cooling with a gaseous fluid can be seen as the first step towards transpiration cooling, which is expected to yield even higher efficiencies due to the evaporation that is associated with it.

In principle the efficiency increase of the entire process is achieved by increasing the difference between the maximum and the minimum process temperature. This means that an increase in turbine inlet temperatures is sought as a contribution to efficiency increase (cf. Fig. 2). It is clear that for the gas turbine in particular impro-

ving only the structural materials will not suffice to control the high operational temperatures of the hot gas. Only by intensively cooling the highly loaded components, for example the blades in the first turbine stage, gas turbine inlet temperatures of near or over the melting point of super alloys are made possible. The efficiency of all cooling technologies, i. e. impingement, convection and film cooling, has been improved during all stages of their development^[7-8]. Transpiration cooling is expected as the advanced cooling technology in the long term.

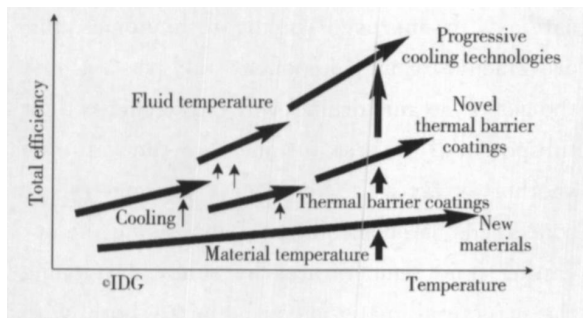


Fig. 2 Efficiency dependence on the inlet temperature of turbine

Film cooling entails the risk of generating (under special operating conditions) local turbulence, which can lead to overheating of the surface. These effects, which reduce the life span of a part significantly, should be avoided by realizing effusion (and in the future transpiration) cooling. The insights gained so far in the research attest that the potential risks can be reduced to a great extent by applying porous cooled structures.

Theoretically, applying ZrO_2 thermal barrier coatings would make an increase in the turbine inlet temperature of 150 K possible, but this potential cannot be used at present, because the life span of these coatings has not yet been reproduced in a quantifiable way. This means that the cooling has to be designed in a way that enables the structural material to withstand the local overheating caused by the blistering of the thermal barrier coating for a certain period of time. By changing to effusion cooling the tendency for blistering should be reduced and at the same time the required amount of cooling fluid should

be decreased. Both will help to increase the power plant efficiency. Only by combining effusion and transpiration cooling respectively with thermal barrier coatings the envisaged efficiency will be attainable.

Figure 3 shows the schematic configuration of a transpiration cooled combustion chamber wall. The structural material supplies the open porous intermediate layer with cooling fluid through a number of chambers. The intermediate layer is protected from the hot gas by a permeable thermal barrier coating. At the surface of the part, i. e. on the hot gas side, the cooling fluid escapes over the whole of the surface, thus ensuring the development of a homogeneous cooling film. The outer layer of a future gas turbine blade could be conceived similarly to the combustion chamber wall. There are two different concepts that could realize such systems. On the one hand hole fields consisting of laser-drilled, contoured holes are investigated, on the other hand open porous metallic foams. A homogeneous cooling film on the surface is achieved by the specified contouring of the holes and their geometrical distribution. The film inhibits the contact between the cooled structure and the hot gas^[9-11].

The method of the porous structures can be realized by the fabric structures in the high temperature area of the steam turbine (Fig. 3, lower left part). The cooling steam could be guided for a convective cooling of the component through sealed porous cavities^[12].

For the extraction of the condensed water in the low-pressure steam turbine a chamber system could be realized as well. For this, the concept of the cooling is turned around and the water is guided through the porous layer in the chambers (Fig. 3, lower right part).

2 MGT/FC hybrid system

MGT/FC hybrid systems up to 10MW could be a promising energy provider in stand-alone applications. They can be applied in residential area as well as in small industry, trade and serv-

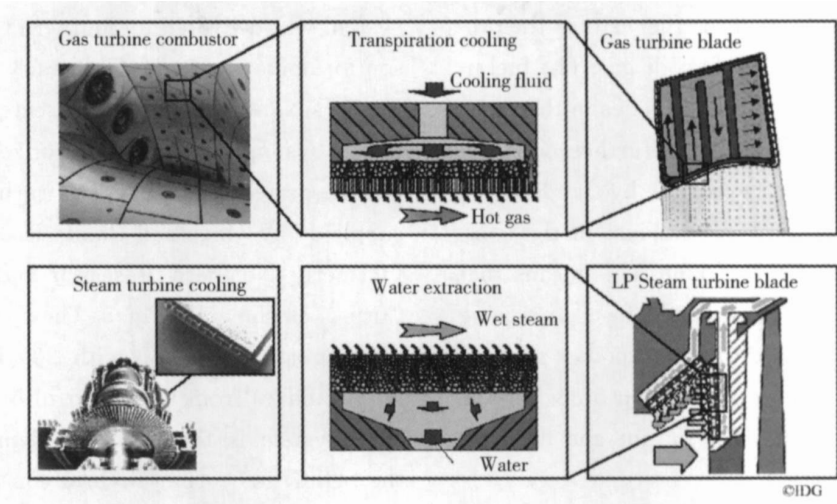


Fig. 3 Illustration of the cooling and water extraction technology in combined cycle power plant

ices or public buildings. 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.

2 1 Basic concept of MGT/FC hybrid system

Studies on plant concepts for SOFC/GT-systems have attracted more attention re-

cently^[13-16]. A hybrid system consisting of a micro turbine and a SOFC (Solid Oxide Fuel Cell) 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.

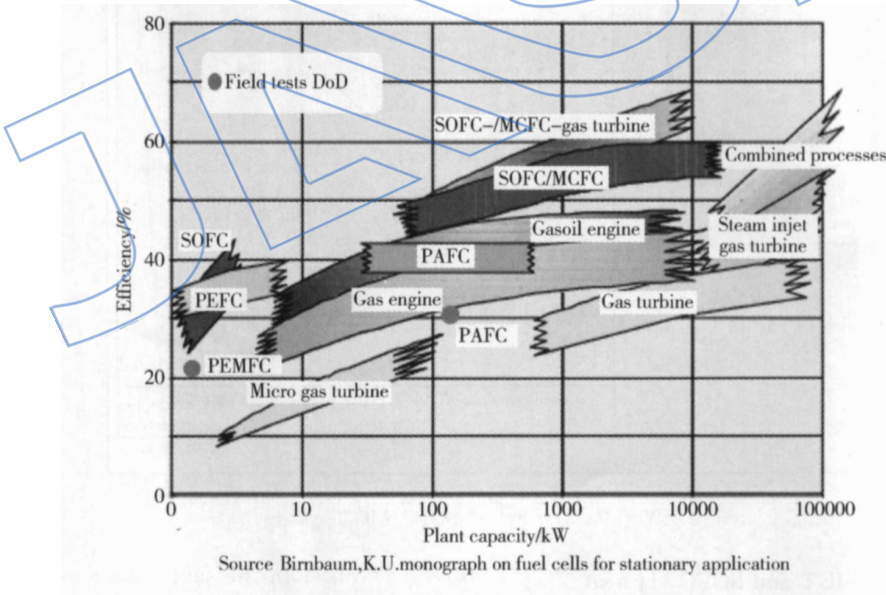


Fig. 4 Relation between plant capacity and electric efficiency

An MGT (Micro Gas Turbine) has a smaller volume and weight but also a lower efficiency (about 30%) and larger emissions than a “normal” gas turbine. Therefore, an MGT working as a stand alone device generates not 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.

Normally, the fuel cell is a SOFC, 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 gas 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 the decentralized power supply. More research needs to be done in order for the FC to increase the specific output and decrease its volume.

It should be mentioned that the estimated efficiency of PEFCs and PAFCs are both somewhat higher than the field test results from the DoD (Department of Defense (UK)), which are marked as green dots in Fig. 4.

2.2 Application of hybrid system

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. 5. The system has a total output of 220 kW, with 200 kW from the SOFC and 20 from the micro turbine generator. This system is the first-ever demonstration of the SOFC/gas turbine hybrid concept. The system was tested at the NFCRC to determine its operating characteristics and operating parameters. Till January 2002 the system had operated for 900+ hours and had demonstrated 53% electrical efficiency. Eventually, such SOFC/GT hybrids should be capable of electrical efficiencies of 60% ~ 70%.

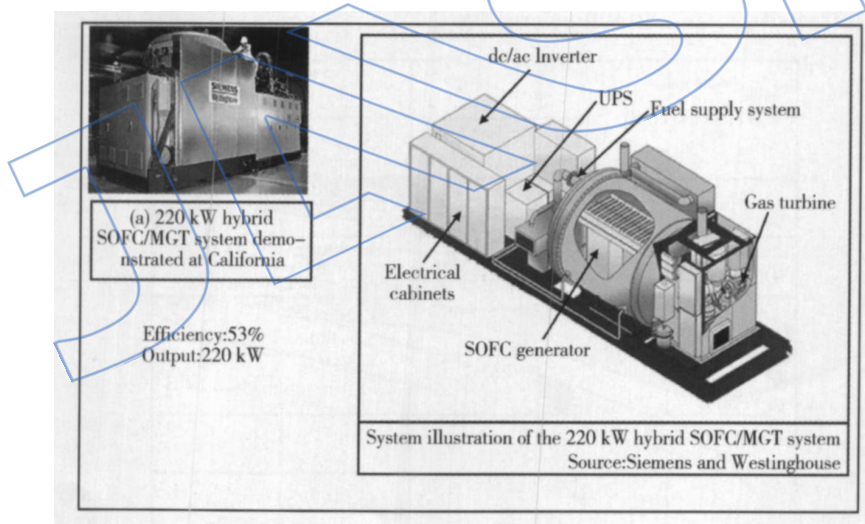


Fig. 5 World's first hybrid SOFC/MGT system

2.3 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 gas heats compressed air in the micro gas turbine recuperator, as shown in Fig. 6. 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^[17]. 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.

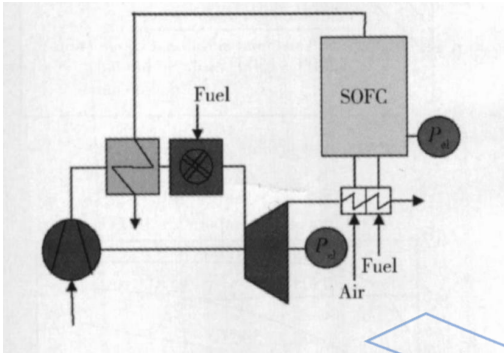


Fig. 6 Integration of a micro turbine and an SOFC by a heat exchanger

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 1 500 °C is assumed, this will lead to system efficiencies as represented in

Fig. 7. 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 the efficiency of this plant concept over the entire investigated range. Pressure optima of systems without additional firing

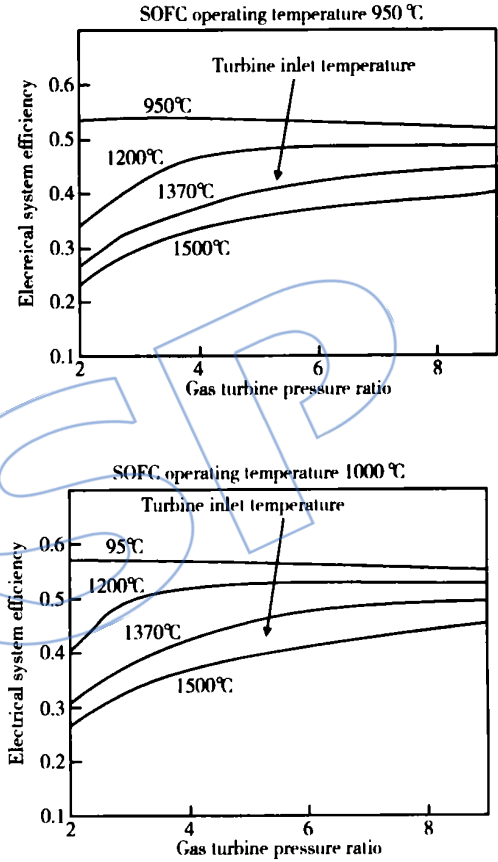


Fig. 7 Integration of SOFC and MGT by heat exchanger: Influence of gas turbine pressure ratio and turbine inlet temperature on efficiency (SOFC operating temperatures are 950 °C and 1000 °C^[20])

are shifted to lower values compared to other studies conducted by e. g. Winkler & Lorenz, 2000^[18]. 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.

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 temper-

atures and turbine inlet temperatures of 1 000 °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 presuppose the possibility of separate operation of the fuel cell and the micro gas turbine, which is facilitated by bypass pipes and valves.

2.4 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 exoegetic 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. The plant concept for this configuration is shown in Fig. 8.

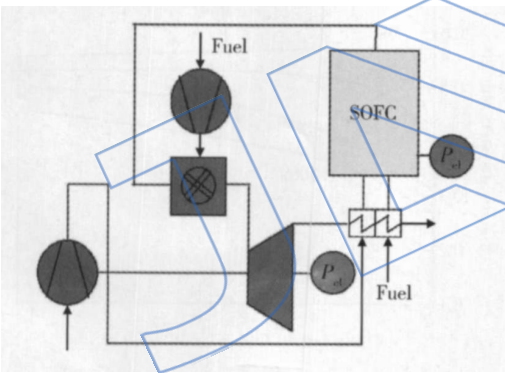


Fig. 8 Direct integration of a micro turbine and an SOFC

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 increase before the hot gases are expanded in the micro gas turbine^[19], yielding a temperature gain of 160 °C at reference point operation ($T_{SOFC}=950\text{ }^{\circ}\text{C}$, $\pi=6.5$).

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 re-

quires increased internal anode and cathode gas recirculating for temperature equalization.

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. 9). In the left graph of Fig. 9, an optimum of effi-

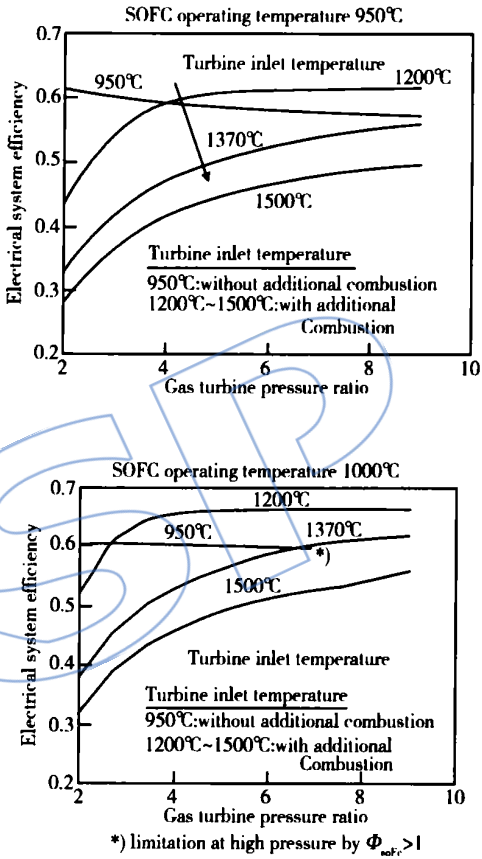


Fig. 9 Direct integration of SOFC and MGT by heat exchanger: influence of gas turbine pressure ratio and turbine inlet temperature on efficiency (SOFC operating temperatures at 950 °C and 1 000 °C^[20])

ciency of the system without additional firing should be expected below the pressure range under investigation. For all scenarios assuming additional firing in the gas turbine combustor, the 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 maximize the efficiency gain. This requires appropriate burner systems, which avoid flashback and ensure stable premixed combustion with a low amount of auxiliary fuel.

2.5 Efficiency improvement of the MGT/FC 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 10 shows an efficiency potential of app. 73% for the new technology. For a turbine inlet temperature of 1 300 °C the optimum SOFC-temperature is 1 060 °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.

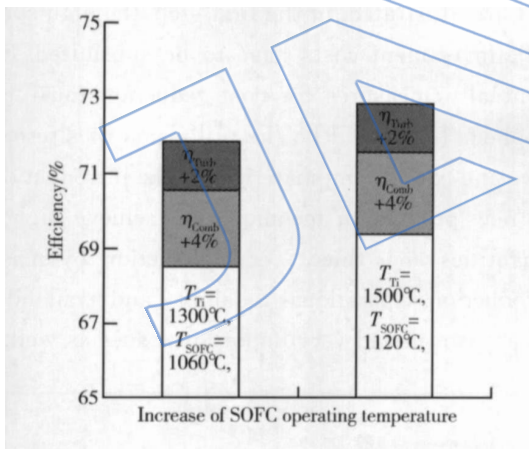


Fig. 10 Influence of the component efficiency improvement to the total efficiency increase

It is shown in Fig. 10 that for a turbine inlet temperature of 1 500 °C the optimum SOFC-temperature lies at 1 120 °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

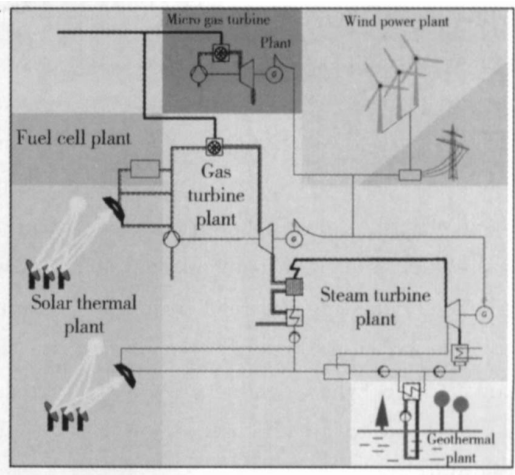


Fig. 11 Hybrid systems with fossil and renewable power plants and boundary conditions for energy supply systems

means that the starting point for the shown efficiency potential is not given at the moment. It is expected that the total efficiency for the direct integration hybrid system will reach 75% in the future.

3 Synergy potential of fossil and renewable power plant technologies

The combination of fossil and renewable power plant technologies contains a large synergy potential to increase the efficiency of processes for power plants. The involved sub processes do not operate separately, but with energetic coupling, so they are called “hybrid systems”.

The most important requirement to such systems is the protection of natural resources and reduction of associated emissions, which can be ensured particularly due to the use of renewable energies as well as the increase of the overall efficiency of the involved systems and components.

Due to innovative and efficient process management high temperature heat from concentrated solar systems can be used to reduce the fuel consumption of gas turbines. Furthermore a high temperature fuel cell plant can be integrated as heat resource into a gas turbine process. For maximum overall efficiency the combustor of the gas turbine has to be replaced by a high temperature fuel cell.

The heat in a water steam circuit can be supplied by solar thermal or fuel cell power plants to provide heat for the high temperature pre heating of the feed water. The low-pressure pre heating can be realized using the coupling with geothermal power plants. The extraction steam, which is used in conventional steam power plants for heating the feed water, can now be used for additional energy conversion in the steam turbine, which leads to a power increase and therewith to an efficiency increase without using more fuel.

The integration of wind power plants with the hybrid process offers useful synergy potential in two different ways:

- Using ingenious dynamic automatic control systems, wind power plants should stay longer at the power grid even at low and high wind speeds.
- Low frequency and power fluctuations in the grid must be guaranteed by a high-quality and fast gas turbine automatic control mechanism.

Achieved results of the research field of wind power plants can be transferred to the production of high strain and extremely light blades in gas turbine compressors, i. e. using textile composites.

Therefore the following items have to be investigated in a hybrid system with fossil and renewable power plants:

- Integration of solar high temperature heat in a natural gas-fired gas turbine.
- Hybrid system gas turbine and SOFC-fuel cell.
- Technical and economical potential of vertical wind power plants.
- Coupling of geothermal plants with a steam turbine plant.
- Coupling of solar thermal plants with a steam turbine plant.
- Model based development and process management techniques with special care of technical parameters and boundary conditions for energy supply systems.

4 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 operations 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. 12 in the next page. In addition to this, the specific investment costs of innovative concepts like photovoltaic and fuel cell technologies increase drastically compared to conventional and well-engineered energy conversion systems like gas turbine technology or combustion engines.

In Fig. 13 possible steps for the introduction of a new technology in the existing energy market are illustrated. In the first step, the high specific investment costs have to be 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 are considered very important issues as well.

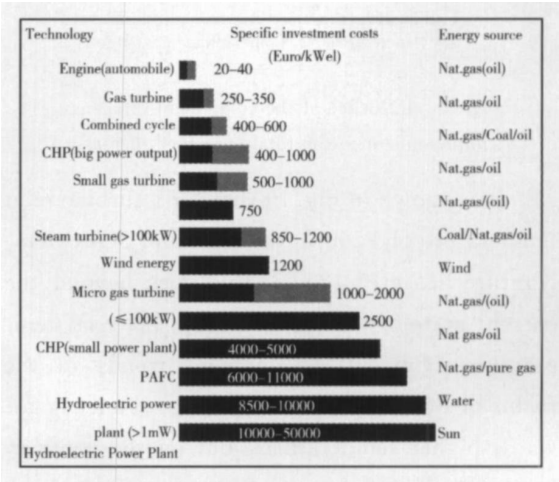


Fig. 12 Specific investment costs and typical primary energy sources for energy conversion

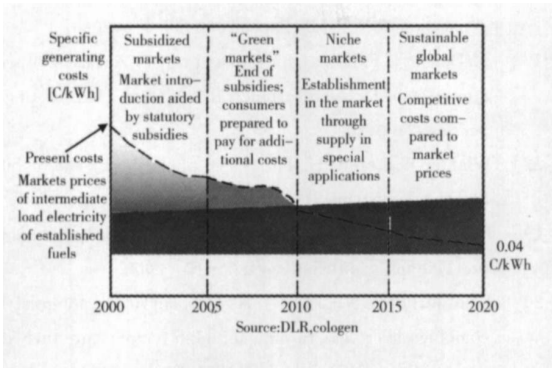


Fig. 13 Steps towards the introduction of new technologies in existing markets

5 Summary

In comparison to conventional systems, with the use of synergetic effects, hybrid systems offer the possibility to provide a substantial contribution to spare our natural resources and improve our environment. It could be a promising way to solve the future energy problem.

The combined cycle power plant belongs to the classic hybrid system and is widely applied to meet the requirements of the centralized energy market. Nowadays the market has a tendency to transform to a decentralized market with new combined heat and power (CHP) units. Hybrid systems containing a number of power generation devices such as wind turbines, photovoltaic, micro-hydro and/or fossil fuel generators are developed to meet such trend. An MGT/FC hybrid system is a typical system for stand-alone applications. Furthermore, the combination of fossil and renewable power plant technologies contains a large synergy potential to increase the efficiency of processes for power plants.

The insight gained so far in research has shown that new materials, innovative cooling technology, new combustion concepts and optimized production methods are needed to make the potential of these new technologies accessible for a quantum leap in efficiency. For this considerable research work and good coordinated research projects between the state, industry, research laboratories and universities is needed.

The consequent further development of efficient design and production processes is the nec-

essary base for the competitive ability of such highly technical systems.

References:

- [1] Bhargava K R. Global energy market[R]. ASME Turbo Expo. Barcelona, Spain, Paper No. GT2006-91322, 2006.
- [2] Smith P C. The environmental challenge bringing technology to market[R]. 17th International Symposium on Air-breathing Engines. Munich, Germany. Paper No. ISABE 2005-1008, 2005.
- [3] Bohn D, Felderhoff M, Lepers L, Moritz N: SFB 561 Energieforschung für die neue Kraftwerksgeneration[R]. von 2020, 7. Internationales Aachener Schweißtechnik Kolloquium, May 2001, Aachen, Germany.
- [4] Bohn D. New materials and cooling systems for high temperature, highly loaded components in advanced combined cycle power plants[R]. 7th Liège Conference on Materials for Advanced Power Engineering, Liège, Belgium, Sept. 30 Oct. 02, 2002.
- [5] Hu W, Gottstein G. Investigation of microstructure and chemical stability on composites of Ni_3Al reinforced by aluminium silica fibres[J]. Elsevier Science, Materials Science and Engineering, 2002, A338: 313-322.
- [6] Schubert F, Mülders B, Herzog R, Singheiser L. Advanced material systems for rotor blades in gas turbines[R]. 10th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery (ISROMAG 10), Honolulu, USA, March 07-11, 2004.
- [7] Laschet G, Rex S, Bohn D, Moritz N. 3D Conjugate analysis of cooled coated plates and homogenization of their thermal properties[J]. Numerical Heat Transfer, Part A, 2002, 42(1): 91-106.
- [8] Bohn D, Moritz N. Numerical parametric study on full coverage cooled multi-layer plates[R]. IGTC 2003 Tokyo TS 084, International Gas Turbine Congress (IGTC) 2003 Tokyo, Tokyo, Japan, November 02-07, 2003.
- [9] El-Magd E, Gebhard J. Characterisation and simulation of the mechanical behaviour of porous multi-layer systems and its components[R]. EUROMAT 2003, Lausanne, Switzerland, September 01-05, 2003.
- [10] Laschet G. Homogenization of the fluid flow and heat transfer in transpiration cooled multi-layer plates[J]. Journal of Computational and Applied Mathematics, 2004, 168: 277-288.
- [11] Pustal B, Böttger B, Ludwig A, Sahm P R, Bührig-Polaczek A. Simulation of macroscopic solidification with an incorporated one-dimensional microsegregation model coupled to thermodynamic software[R]. In: Metallurgical and Materials Transactions, Carnegie Mellon University, Pittsburgh, Pennsylvania, USA, 2003.
- [12] Dilthey U, Ghandehari A, Kopp R, et al. Development of porous steel structures for steam turbines[J]. Advanced Engineering Materials, 2001, 3: 111-119.

- [13] Veyo S L, Shockling L A, Dederer J T, et al. Tubular solid oxide fuel cell/gas turbine hybrid cycle power systems status[R]. ASME Paper 2000 GT-0550, München, 2000.
- [14] Bohn D, Krüger U, Lepers J, Sürken N. Kopplung von Mikro Gasturbinen und Brennstoffzellen Potenziale für die stationäre Stromerzeugung[R]. BWK, 2000, 52, 5.
- [15] Campanari S, Macchi E. Performance prediction of small scale tri-generation plants based on integrated SOFC and microturbine systems[R]. ASME Paper 2000 GT-0318, 2000.
- [16] Massardo A F, McDonald C F, Korakianitis T. Microturbine/fuel cell coupling for high efficiency electrical power generation[R]. ASME Paper 2000 GT-175, 2000.
- [17] McDonald C F. Low-cost compact primary surface recuperator concept for microturbines[R]. Applied Thermal Engineering, 2000, 20.
- [18] Winkler W, Lorenz H. The design of stationary and mobile SOFC GT systems[R]. 7th UECT, 2000.
- [19] Pålsson J. Thermodynamic analysis of combined solid oxide fuel cell and gas turbine systems[R]. 2000.
- [20] Bohn D, Pöppe N, Lepers J. Assessment of the potential of combined micro gas turbine and high temperature fuel cell system[R]. VDI Bericht NR. 1714, Bochum, 2002.