

Review

Theoretical and Experimental Studies of Combined Heat and Power Systems with SOFCs

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Abstract: The article presents an overview of experimental layout design solutions and the general operation scheme of combined heat and power systems with a high-temperature solid oxide fuel cell (SOFC). This system is an environmentally friendly and energy-saving way to produce electricity and heat. The use of high-temperature SOFCs makes it possible to obtain an electrical efficiency of 45–55%. Combining the electrochemical and mechanical system can increase the total efficiency by up to 60–65% in a hybrid power plant. This article discusses the structure and relationship between the components of a hybrid power plant and various modification options for efficient power generation. The technological schemes for existing and tested hybrid power plants with an SOFC and gas turbine are presented and described in detail. When designing a hybrid power plant, the key factors are the choice of design, heat source, and fuel-reforming method; the design of a solid oxide fuel cell and the number of modules in a stack; selecting devices for generating electricity with the development of cogeneration or trigeneration cycles (for possible use in thermal power plants and for the energy supply of social facilities); the direction of material flows within the system; pressure and tightness; and the interconnection of the hybrid power system elements. Researchers have accumulated and described in scientific papers extensive experience in designing, theoretical research, and numerical modeling of hybrid power plants with high-temperature SOFCs. It is shown that experimental hybrid power plants based on SOFCs of the megawatt class are in operation. Hybrid systems with an SOFC are designed only for the kilowatt power class. Trigeneration systems with a steam turbine exist only in the form of theoretical calculations. Trigeneration systems show the highest electrical efficiency, but the highest construction and service costs. Systems based on high-temperature SOFCs can be used for autonomous systems, and in combination with gas and steam turbines only at thermal power plants. Experimental laboratory studies are limited by the high cost of installations and the difficulties of testing the possibility of using combined heat and power systems on an industrial scale. Therefore, a more detailed study of the relationship between the units of a combined heat and power system is recommended in order to achieve the high efficiency indicators obtained from theoretical studies.

Keywords: solid oxide fuel cell (SOFC); gas turbine; combined heat and power systems; hydrogen energy



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1. Introduction

Environmental and climate change, issues and problems of fuel resources distribution, politics, and economics force researchers to develop alternative environmentally friendly, efficient, and resource-saving methods for electrical and thermal energy production [1]. Researchers and scientists worldwide have been striving to solve this problem over the past decades. The change in demand for energy resources towards the use of alternative

energy requires the formation of a new energy system based on the latest achievements of science, engineering, and technology. Hydrogen energy is no exception in this matter.

Hydrogen, when burned directly, is a difficult-to-control and explosive gas. Therefore, it is proposed to obtain energy from hydrogen fuel using electrochemical conversion in a fuel cell [2]. Combined heat and power systems are the most efficient way to use hydrogen fuel. They are equipped with an electrochemical and mechanical generator and combine the operation of an SOFC with a gas turbine [3]. The idea of combining the two cycles is based on the concept of replacing the combustion chamber of a gas turbine engine operating on the Brayton cycle with a fuel cell. SOFCs provide direct electrochemical electricity production instead of classical combustion and subsequent conversion of mechanical energy into electrical energy. The heat produced in this process is used to rotate a turbogenerator, which generates an additional 20% of the plant's total electrical output. During the operation of combined heat and power systems with SOFCs, emissions of harmful substances are significantly reduced and total efficiency is increased by up to 60% or more [4,5].

An important advantage of combined heat and power systems with SOFCs, in addition to high total efficiency, is the possibility of utilizing hydrogen-containing gases (industrial and social waste) instead of burning them in the atmosphere. Hybrid power plants are equipped with carbon dioxide capture technologies to ensure the decarbonization of the electricity production process [6].

Since the idea of “hybridizing” a fuel cell and a gas turbine came about (in the mid-1970s), a large number of hybrid power plant concepts have been patented. The concepts differ in the type of fuel cell, the layout of the system, and the operating pressure and temperature [7]. In addition to the gas turbine, a gas-piston engine can operate as part of a hybrid power plant, and combinations with a steam turbine are also offered. Several studies of SOFC/GT hybrid power plants demonstrate the possibility of including an additional thermodynamic cycle due to the high temperature of the exhaust gases. This has led to increased interest in the possibilities of integrating SOFCs, gas turbines, steam turbines, chillers, solar panels, electrolyzers, desalination plants, and other installations into a single combined cycle with ultrahigh efficiency [8–10].

The scientific community has accumulated considerable experience in designing and optimizing the operation of hybrid systems based on the integration of SOFCs and gas turbines, along with other cogeneration and trigeneration cycles to create combined heat and power systems [11]. Experimental studies on laboratory and pilot models of hybrid power plants are not so extensively described in the scientific literature. This is due to the high capital costs required to create prototypes, even on a laboratory scale [12].

An extensive part of the scientific research is aimed at studying the characteristics and operating modes of hybrid systems using various types of fuel, mainly hydrogen. The spheres, features, and possibilities of using hybrid systems at thermal power plants are discussed poorly. In addition, there is no comparison of the capabilities of hybrid systems with different layouts for combined heat and power generation in the energy sector.

The purpose of this article is to review pilot and industrial projects of combined heat and power plants with a solid oxide fuel cell and a gas turbine as an environmentally friendly and energy-saving way to produce electrical and thermal energy. Experimental and simulated hybrid power plant projects were analyzed in terms of energy and economic performance indicators. Particular attention was paid to identifying differences in the projects under study. This article will be useful for manufacturers and the scientific community, as it presents possible layout options for a hybrid power plant and original design solutions.

2. Layout and Schematic Diagrams of Hybrid Power Plants with SOFC

The following key processes take place in a hybrid electrochemical–mechanical installation: fuel purification and reforming, electrochemical conversion, afterburning, and mechanical cycle in a gas/steam turbine. The choice of a layout for a hybrid power plant with an SOFC depends on many design parameters, such as fuel type, SOFC operating tem-

perature and pressure, the relationship between the SOFC and GT, heat recovery options, etc. [12].

The optimal solution for hybrid power plants is the use of high-temperature fuel cells (fuel cells on molten carbonates and solid oxide fuel cells). SOFCs can operate on any gaseous and liquid hydrocarbon fuel (hydrogen, natural gas, propane, biogas, diesel fuel, aviation kerosene, etc.) and, in terms of its operating parameters, is most suitable for use in large-scale power plants. The electrical efficiency of an SOFC is 45–55%. In the case of further utilization of thermal energy in combined cycle plants, the efficiency can reach 65% and higher. The operating temperature varies from 600 to 1000 °C. Solid zirconium stabilized with yttrium is used as an electrolyte [13].

Hydrogen and oxygen involved in electrochemical reactions in SOFCs are obtained after purification and reformation of hydrocarbon fuel and air. Reforming in SOFCs can be internal or external [14,15]. External reforming is often used to process complex fuels (biogas, waste gas). The process of endothermic steam reforming and the electrochemical reaction in SOFCs are carried out in different units, without direct heat transfer. During internal reforming, the endothermic steam-reforming reaction is carried out in conjunction with the exothermic oxidation reaction in the anode compartment, or with the heat exchange between the compartments [16,17]. Internal reforming makes it possible to provide anode off-gas heat utilization and is more preferable if methane or natural gas is used as a fuel [18,19]. The performance of SOFCs and hybrid power plants significantly depends on the reforming method used [20].

During the electrochemical reaction in an SOFC, a large amount of heat is released. A significant amount of heat is released, which can be beneficially used for cogeneration purposes (hot water production, district heating, steam production, etc.) [11,12,21]. It is possible to use hybrid power plants with SOFCs in auxiliary systems of thermal power plants. At the same time, it is possible to partially replace the heat exchangers for network water heating at TPPs with heat exchangers that use the heat produced by a hybrid power plant. Thus, it is possible to organize the parallel operation of the Rankine cycle and the thermodynamic cycle of a hybrid power plant [22].

Owing to the limited availability of experimental studies of hybrid power plants, the methodology and methods for their calculation are based, in this case, on numerical simulation.

The energy balance of a hybrid power plant is described by the following equation:

$$m_{air} \times h_{air} + m_{f,SOFC} \times \beta_f \times L_f + \int \frac{dQ_{CC}}{dt} - m_{EG} \times h_{EG} - \int \frac{dQ_{loss}}{dt} - P_{SOFC,DC} - P_{GT} = 0 \quad (1)$$

m —mass flows, kg/h; h —enthalpy, J/kg; β_f —SOFC fuel utilization factor; L_f —lower calorific value of fuel, MJ/kg; P —power, kW; f —fuel; CC—combustion chamber; GT—gas turbine; DC—direct current; EG—exhaust gases.

The electrical efficiency of a hybrid power plant is calculated as follows:

$$\eta_{el} = \frac{P_{net}}{P_{tp}} \quad (2)$$

P_{tp} —total power of energy supply to the system, W; P_{net} —net output electric power, W, where

$$P_{net} = \eta_{inv} \times P_{SOFC,DC} + \eta_{gen} \times P_{GT} \quad (3)$$

η_{inv} , η_{gen} —efficiency of inverter and generator.

$$P_{total} = m_{f,SOFC} \times \beta_f \times L_f + P_{CC} \quad (4)$$

Figure 1 shows the schematic diagram of an SOFC with steam reforming, operating on natural gas. A power plant with an SOFC can be used as a micro-combined heat and power (CHP) plant for housing and social facilities. In this technological scheme, a kilowatt-class SOFC operates as follows: natural gas is preliminarily purified (desulfurization stage), and

then it is fed into the reformer for conversion into synthesis gas and fed into the SOFC stack to produce electrical and thermal energy. The exhaust gases from the anode and cathode chambers of the SOFC contain unreacted air and fuel residues and are sent to the post combustor for afterburning. After the post combustor, gases with a temperature of 900–1000 °C are sent to preheat the inlet fuel and air streams, produce steam, and heat the fuel-reforming reaction [23].

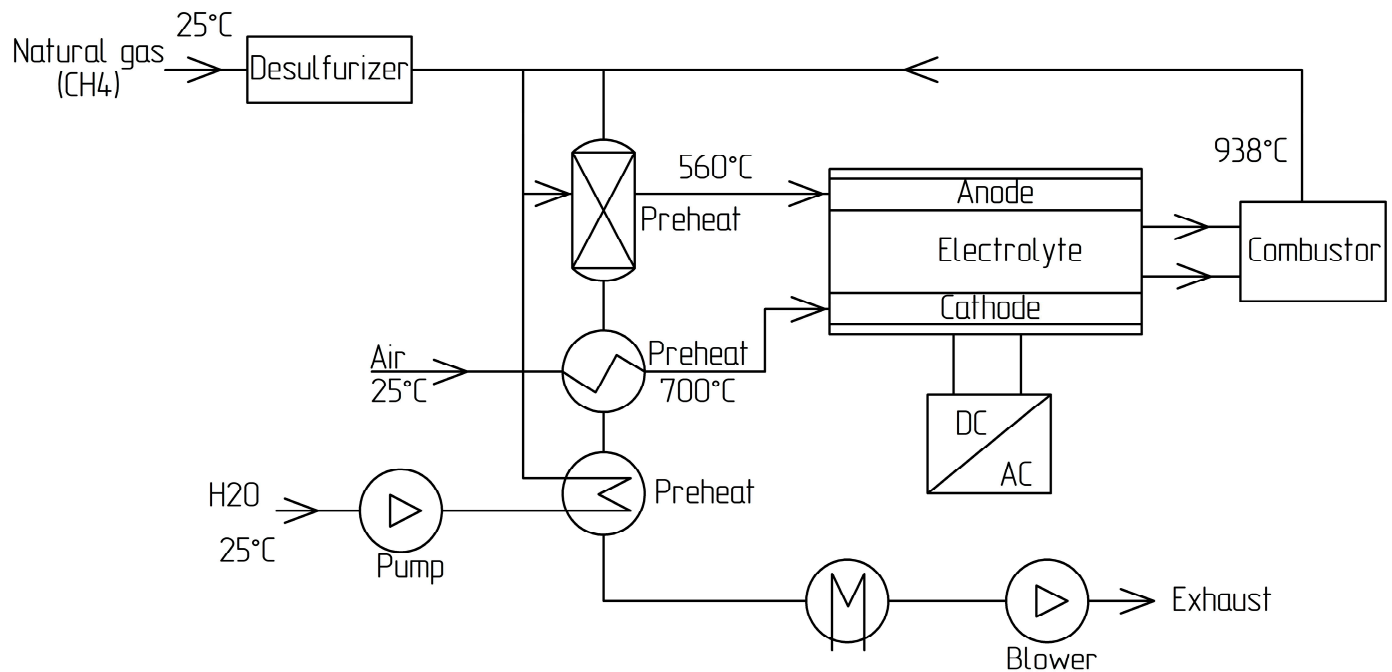


Figure 1. Schematic diagram of an SOFC operating on natural gas that can be used as a micro-combined heat and power (CHP) plant.

After heating the inlet gas and air flows and heat transfer in the steam generator, the heat of the exhaust gases is transferred to the heating network with a temperature level of 30–60 °C for residential heating and 80–130 °C for industrial heating networks. The heat exchanger at the end of the circuit cools the exhaust gases, after which the blower creates a pressure difference in the cold exhaust gases to pass the gas flow through the entire system.

The temperature of the gases at the outlet of the electrochemical system does not exceed 300 °C. This circumstance makes it difficult to use SOFCs as a heat source for the secondary thermodynamic process. Researchers have developed design solutions that allow combining a fuel cell and a gas turbine with thermal gas flows. Thus, the heat generated by both units is effectively used for fuel and air heating, for fuel reforming, etc. SOFC efficiency can be increased by using a gas turbine to supply cathode gas instead of an air compressor [24].

The operating pressure of the fuel cell significantly affects the efficiency and reliability of the system. The operation of a fuel cell at atmospheric pressure is characterized by its simplicity and reliability. In this case, the SOFC is completely autonomous and connected to the gas turbine by a heat exchanger.

When an SOFC is operated at high pressure, electrochemical losses decrease and output power and efficiency increase (and electrochemical kinetics improve). In this case, the SOFC operates as a GT combustion chamber, which limits the area of SOFC/GT systems operation [25].

The technological scheme of a hybrid power plant includes the following auxiliary equipment, which provides a connection between units and efficient heat flows transfer: compressors, ejector, heat exchangers, recuperator, combustion chamber, and fans [21,22,26].

Electricity generation at gas turbine power plants has an efficiency of 29–45%, depending on the operating parameters of a particular turbine model and fuel characteristics. Reference [27] proposes the integration of an SOFC with a gas turbine power plant with an efficiency of 30% to increase energy production and system efficiency. The SOFC capacity is 9.3 MW and the total capacity of the hybrid system is 18.9 MW. It is proposed to connect the units in a hybrid system as follows: the exhaust gases from the GT are used to preheat the SOFC reactants, the exhaust gases from the SOFC stack are used to preheat the gases entering the turbine. Preheating the gases at the inlet of the fuel cell increases its operating temperature and therefore leads to better performance. Preheating the gases entering the GT combustion chamber reduces the amount of fuel required for the gas turbine power plant. Thus, SOFCs and GTs mutually contribute to improved performance (Figure 2).

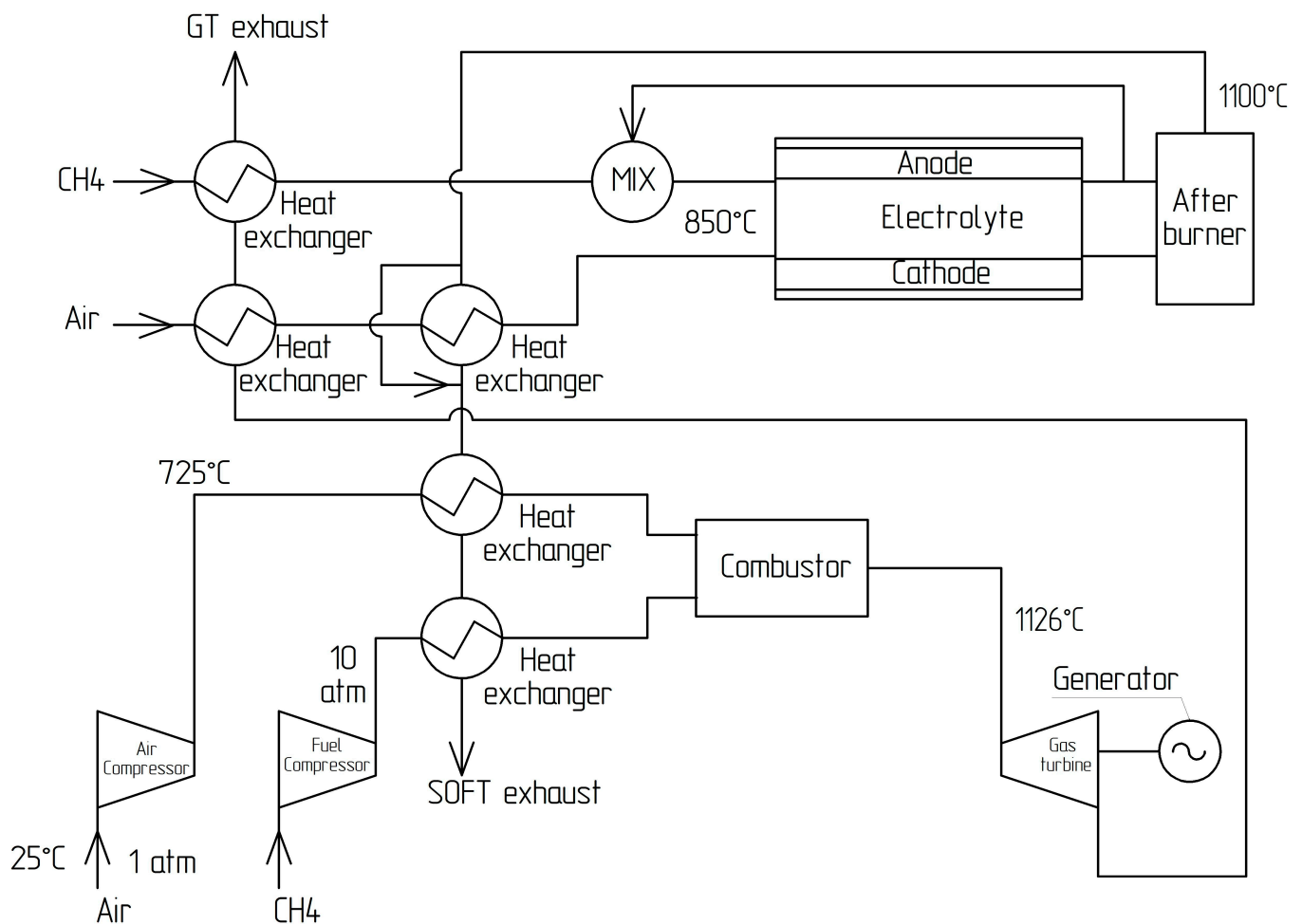


Figure 2. SOFC/GT hybrid plant (18.9 MW).

Research results show that the overall system efficiency increases from 30% to 48.5%, and the cost of electricity generation decreases from 5.46 to 4.54 cents per kWh.

Alexandros Arsalis et al. investigated the possibility of creating a large energy system for use in thermal power plants and for the energy supply of social facilities [28]. The technological scheme of the combined heat and power system proposed by the authors includes an SOFC, a gas turbine, and a steam turbine. It is a trigeneration cycle, which is suitable for large power capacities and can be used at thermal power plants. The SOFC has a tubular configuration developed by Siemens. The electrochemical plant includes a fuel reformer and it is also equipped with anode off-gas recirculation (Figure 3). Hybrid plants with the following capacities were considered in the paper: 1.5, 5, and 10 MW. The authors concluded that the SOFC–gas-turbine–steam-turbine hybrid configuration can be

used for ultraefficient power and heat generation. For example, a 10 MW hybrid plant has a maximum efficiency of 73.7%. For a 1.5 MW system, the SOFC–gas-turbine–steam-turbine cycle is not as efficient as for a 5 or 10 MW system because small gas turbines, and especially small steam turbines, are not very efficient.

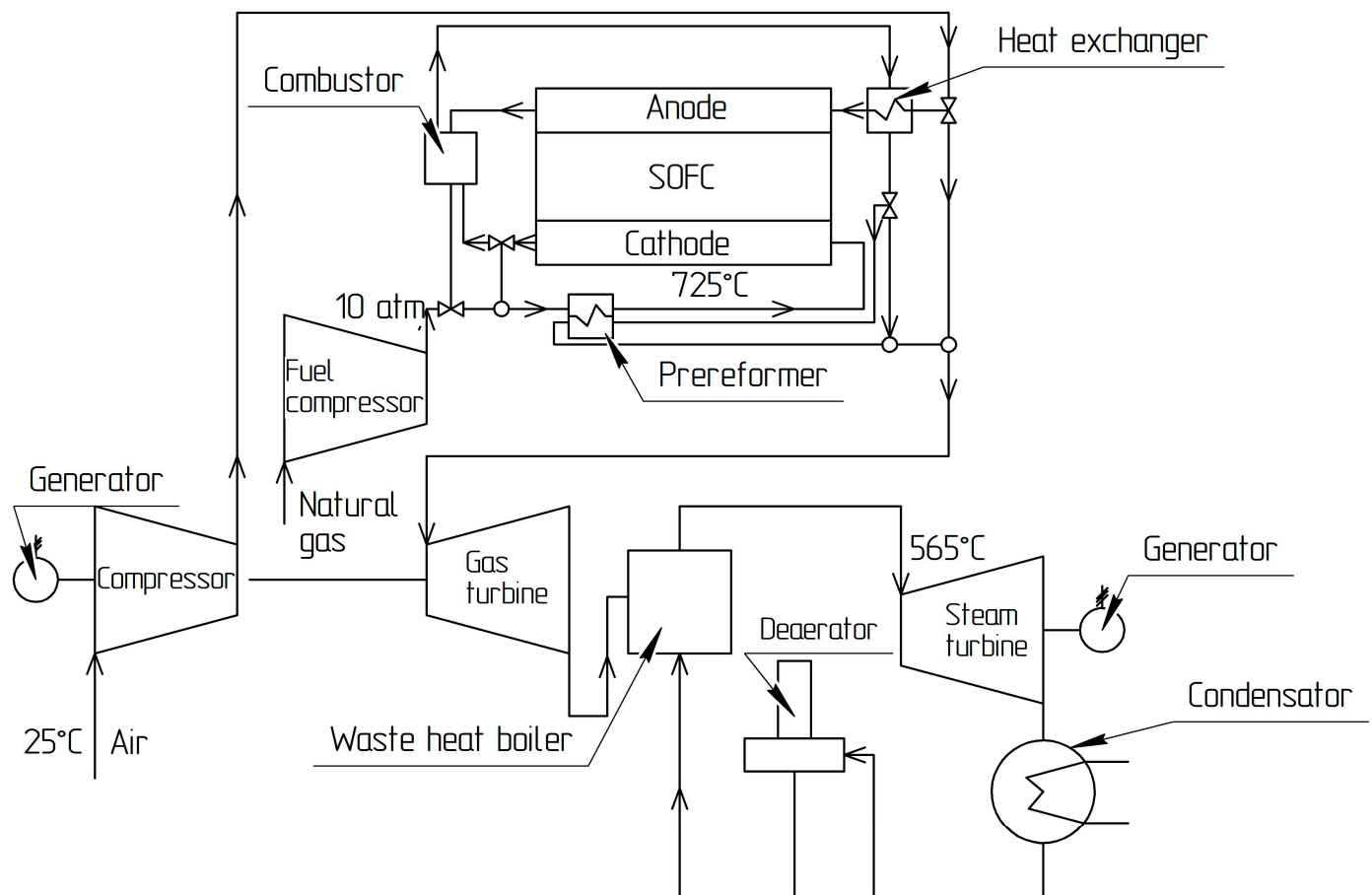


Figure 3. Schematic diagram of the SOFC–gas-turbine–steam-turbine combined cycle.

Thus, it can be concluded that the efficiency of combined heat and power systems with an SOFC depends on the layout, size, and power of the installations included, the presence of an additional combustion chamber, etc. For a kilowatt-class hybrid power system in the range from 250 kW to 1 MW, the efficiency is 55–60%. In an SOFC/GT hybrid system with a power of 5–10 MW, the electrical efficiency reaches 68%. Thermal and electrical overall efficiency is 85–90%. NO_x emissions depend on the presence of a combustion chamber. However, NO_x emissions are significantly lower than during gas turbine operation [12].

The transition from theoretical calculations to industrial implementation of hybrid power system projects is associated with difficulties of connecting the SOFC with a gas/steam turbine, fuel reforming, aspects of the control system, and equipment cost.

3. Projects of Pilot and Industrial Hybrid Power Plants

Several conventional heat engines (gas turbines, steam turbines, and gas-piston plants) are considered in the literature for integration with SOFCs in a hybrid cycle [5]. Hybrid power generation systems have been developed and industrially tested in combination with gas turbines only. Combining the electrochemical and mechanical cycles into a single system makes it possible to implement the following aspects:

1. The possibility for supplying SOFC exhaust gases to the GT due to the consistency of temperature and pressure of gas flows;

2. The waste heat recuperator of the SOFC can be used to supply gases to the GT combustion chamber;
3. The gas turbine allows the fuel cells to operate at a higher pressure, which improves fuel cell stack performance;
4. The thermal energy contained in the SOFC exhaust gases increases the efficiency of the GT. This energy can be used in a compressor to pressurize the hybrid system and in an electrical generator to produce additional electricity;
5. The capacity of commercially available fuel cells corresponds to the size of existing gas turbines.
6. The best-known pilot project is the 220 kW Siemens Westinghouse SOFC/GT hybrid power plant installed at the University of California (Figure 4). This system was the first relatively powerful example of SOFC/GT hybrid technology. Another similar Siemens Westinghouse hybrid power plant achieved power of 300–1000 kW with an electrical efficiency of 55–60% and an overall efficiency of more than 75% [29].

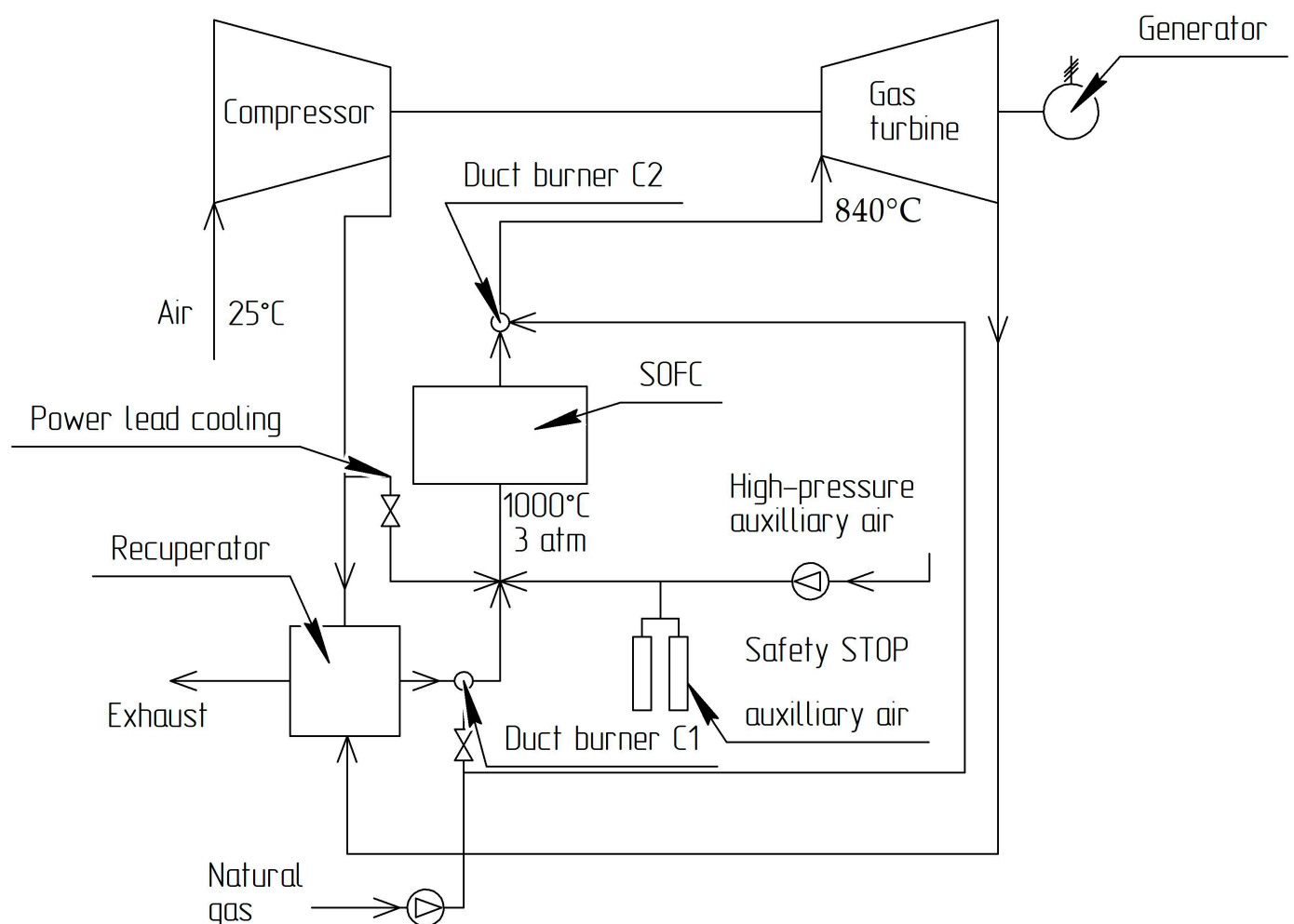


Figure 4. Technological scheme of the Siemens Westinghouse SOFC/GT hybrid power plant.

The SOFC stack consists of vertically mounted, tubular fuel cells operating in a series/parallel configuration. The gas turbine had a power of 75 kW.

A simplified layout of a 220 kW SOFC/GT prototype system is shown in Figure 1. The air is filtered and compressed to approximately 3 bar in the gasifier. The air is then preheated in the heat exchanger by the low-pressure turbine exhaust gases and enters the cathode compartment of the fuel cell. Natural gas is compressed and then desulfurized. Natural gas is used for the anode compartment of the fuel cell and is also supplied to two

auxiliary combustors located upstream and downstream from the SOFC stack. Natural gas is reformed in the SOFC and also converted into electricity through an electrochemical reaction. The SOFC exhaust gases are initially expanded in the high-pressure turbine, driving the air compressor and then in the low-pressure turbine, driving the generator, producing additional electrical power. The operating temperature of the SOFC is about 1000 °C, while the operating pressure is about 3 bar. The system works under joint pressure. The air leaves the heat exchanger at a temperature of about 550 °C.

The net power generated by the gas turbine was about 20–30 kW AC. This is due to the low temperature at the turbine inlet (700–800 °C). The temperature was below nominal (871 °C) due to the excess power of the selected gas turbine.

The power of the SOFC and gas turbine was 172 and 22 kW-DC, respectively. The AC efficiency of the installation was about 52.1%. The researchers concluded that the overall efficiency of the plant was greatly affected by the excess capacity of the gas turbine due to suboptimal system design. Commercially available gas turbines were too powerful, resulting in excess airflow through the bypass. The air passing through the bypass mixed with the SOFC exhaust gases and led to a low temperature at the turbine inlet. The temperature was insufficient, so the efficiency of the gas turbine was less than expected. The overall system efficiency was also affected by the low voltage of the second row of the SOFC stack. As a consequence, the electrical efficiency obtained during the tests (52%) was lower than expected (>57%).

Another important test of an SOFC/GT hybrid system was conducted by Mitsubishi Heavy Industries. The operating principle of the system was basically similar to the Siemens project. The hybrid power plant with a tubular SOFC had an operating temperature of about 1000 °C and a total power of 200 kW [30].

The main differences of the Mitsubishi hybrid plant (Figure 5) are the following: anode gases are recirculated using a high-temperature fan instead of using an ejector; combustion of the anode and cathode exhaust gases takes place in an external combustion chamber, compared to the internal combustion used in the Siemens plant. A special combustion chamber was designed to operate with the exhaust gases of SOFC, whose calorific value is one-tenth of the calorific value of natural gas.

The system achieved a power efficiency of 52.1% at the operating point with a net power output of 204 kW-AC, which is at the highest level in its class. This prototype was conceived as a small-scale project, proving the possibility of creating larger systems that the company plans to develop.

Rolls-Royce Fuel Cell Systems (RRFCS) has been developing SOFC technology since 1992 and has made significant progress in this area. The 1 MW SOFC system concept was designed, tested, and commissioned in 2008. This system consists of a generator module (which includes a stack of fuel cells), a turbogenerator, a fuel processor, and a power electronics subsystem. The 1 MW hybrid power plant comprises four 250 kW generator modules [31]. The layout of the RRFCS SOFC/GT hybrid power plant is relatively simple due to the limited number of components, although the interaction between them is quite complex. The second generation plant is planned to be more powerful and have a greater electrical efficiency compared to the first generation plant [32].

RRFCS second generation SOFC/GT plant configuration uses ejectors to utilize the anode and cathode off-gases, eliminating the need for high-temperature fans. It was planned to model and design a new two-stage turbocharger. However, owing to the pressure drops caused by the ejectors, the net capacity of the turbocharger will be lower than the capacity of the SOFC. Currently, no data have been published regarding the operation of the prototype.

A similar project was also presented by the Allison Engine Company. A hybrid power plant with an SOFC/GT was created and researched. At the operating point, the pressure coefficient was 7.0, the electrical efficiency was 67.0%, and NO_x emissions were less than 1 ppm. Further improvement in the layout can lead to an increase in efficiency by 3.0%.

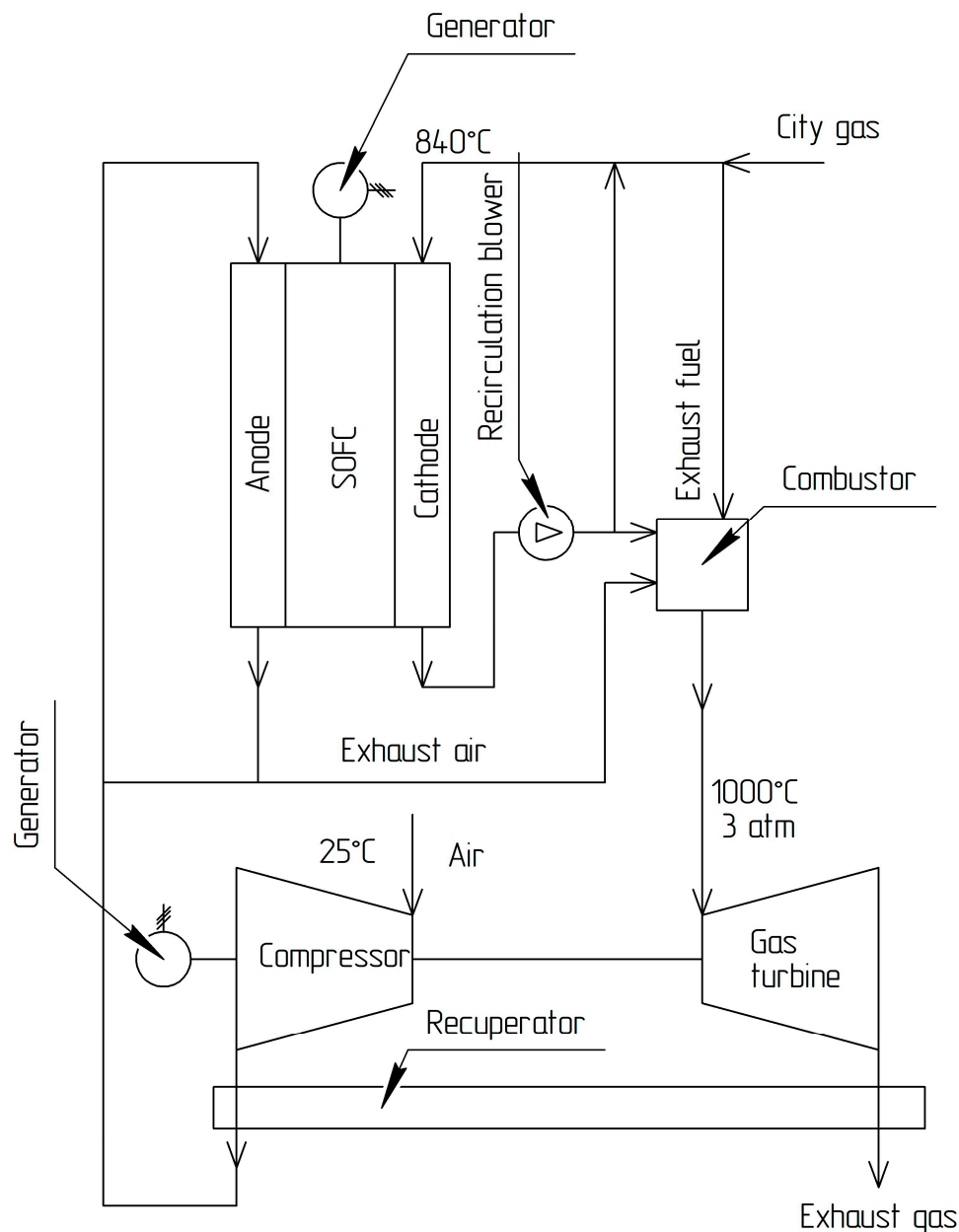


Figure 5. Technological scheme of the 200 kW Mitsubishi SOFC/GT hybrid power plant.

McDermott Technology has also developed a concept design of a planar SOFC stack for a fuel-cell/gas-turbine hybrid system. The hybrid power plant was supposed to generate 700 kW of electricity with an electrical efficiency of 70% [33]. Unfortunately, experimental data on the projects of Rolls-Royce, Allison Engine Company, and McDermott Technology have not been published.

Another small-capacity SOFC/GT prototype was tested in Korea [34]. KIER researchers designed and commissioned a 5 kW planar solid oxide fuel-cell/gas-turbine power generation system with a pre-reformer. The SOFC stack was manufactured by Forschungszentrum Jülich (Jülich, Germany), while the hybrid power plant was assembled and installed at KIER. The authors compared the performance of the SOFC stack in two operating modes: atmospheric, without integration with GT; under pressure, integrated with GT. The capacity of the SOFC plant for hydrogen as a fuel at atmospheric pressure was 8.1 kW and 4.7 kW for pre-reformed gas.

The system layout was based on the integration of an externally reformed planar SOFC with a recuperative gas turbine, as shown in Figure 6. Liquefied natural gas was

supplied to the pre-reformer. The SOFC had a power of 5.1 kW at a pressure of about 3.5 bar. The power of the gas microturbine was 25 kW. Based on the test results, the authors concluded that the planar SOFC with recirculation of anode gases successfully operates in a pressurized hybrid system with a gas microturbine. The authors of the study reported achieving a fuel utilization rate of 33.2%. However, data on the efficiency of the entire system and the amount of electricity generated by GT are not provided.

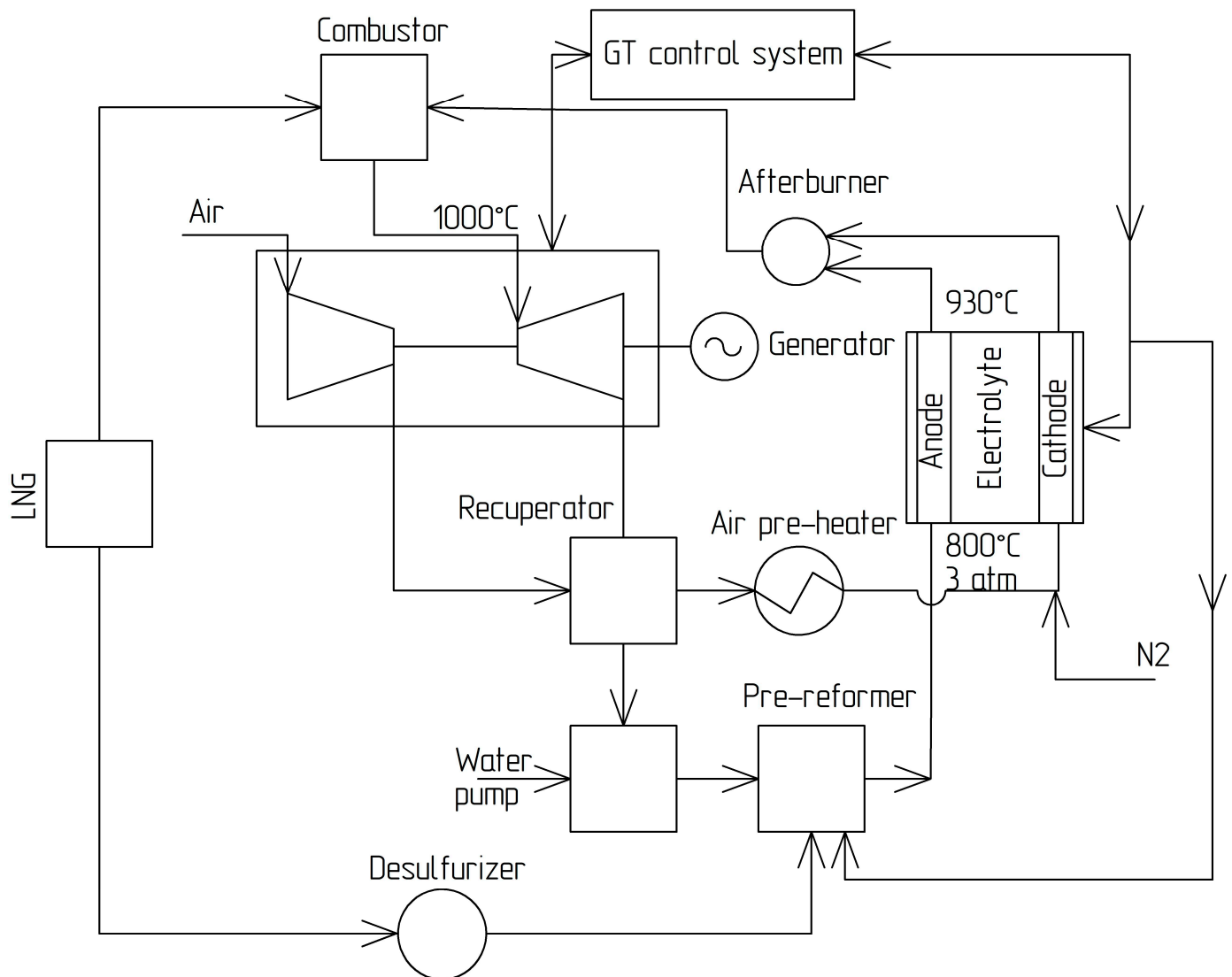


Figure 6. Technological scheme of the KIER SOFC/GT hybrid power plant.

Currently, several hybrid systems are being created:

1. SOFC/GT to replace the auxiliary power unit of the Boeing 777–200 aircraft platform, with a total power of 432.1 kW, SOFC power of 347.0 kW, GT power of 84.2 kW, and autothermal fuel reforming;
2. Hybrid power plant in Woburn, Massachusetts, USA (ZTEK Corporation) with a capacity of 200 kW;
3. Delphi experimental hybrid power plant with a capacity of 50 kW. The goal is to develop an Integrated Gasification Fuel Cells Power Plant (IGFC) with power above 100 kW at a total electrical efficiency of at least 50%, which is equipped with carbon dioxide capture technologies [20].

In addition, hybrid system emulators have been developed that contain various parts of a complete hybrid power plant. Missing components (usually a fuel cell stack) are emulated to account for the effects of that component on the operation of the entire system [32]. For example, the German Aerospace Center (DLR) has made a significant contribution to the development of SOFC/GT hybrid technology. Two hybrid systems emulators were created and commissioned. High-pressure tests were carried out on solid oxide fuel cell stacks. DLR plans to build and operate a fully integrated prototype SOFC-GT hybrid power plant with an electrical output of 30 kW (Figure 7) [35].

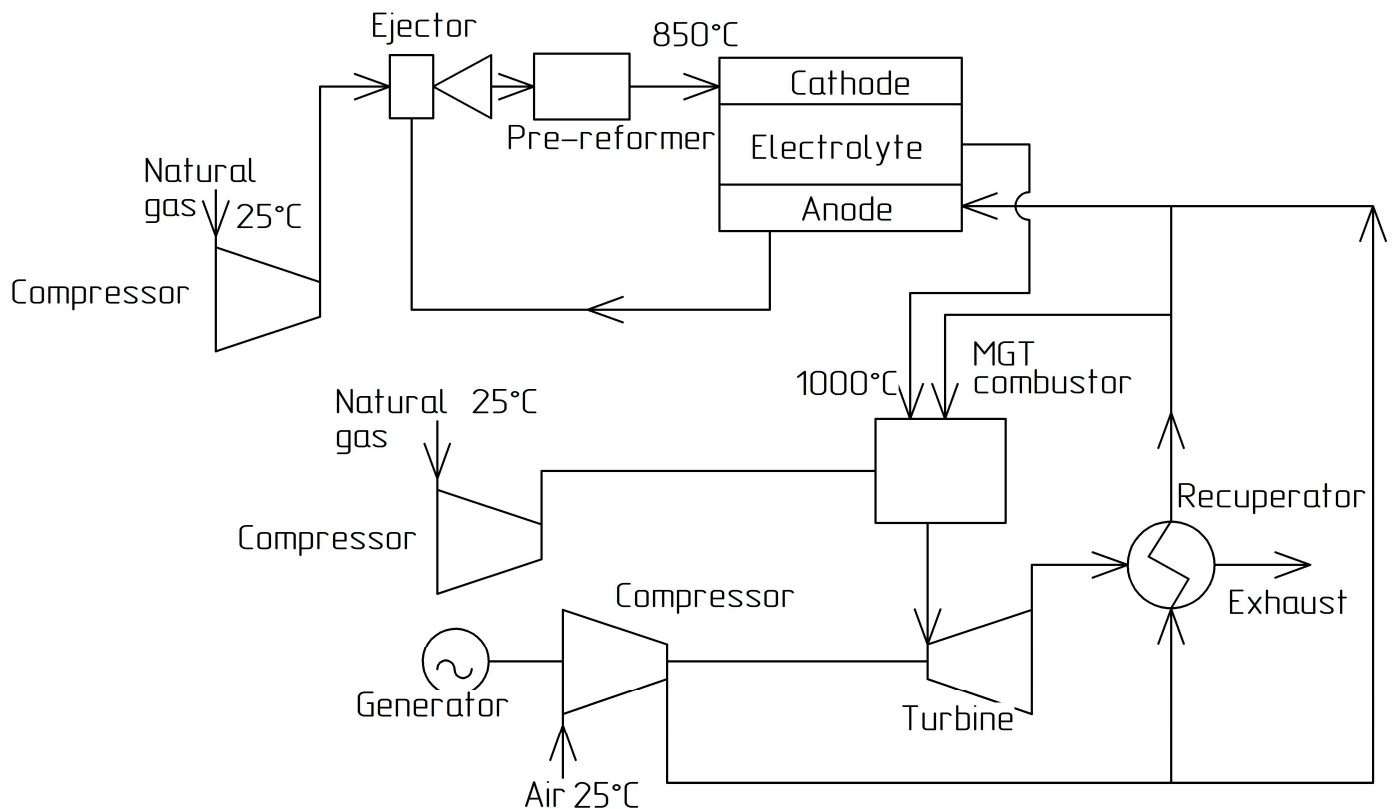


Figure 7. Hybrid power plant layout.

4. Challenges of the Hybrid Systems

Combined heat and power systems with an SOFC and gas turbine have attracted significant interest from researchers, industry, and energy companies in recent decades. However, it is not possible to commercially implement combined energy production systems due to a number of economic and technological difficulties.

Several papers present detailed economic analysis of the various components and production processes of a combined heat and power system with an SOFC and gas turbine. The cost of six microturbines with a capacity of 30–1000 kW was analyzed. Their cost varies from USD 1251/kW (1000 kW) to USD 1896/kW (30 kW) for power generation installations. If the hybrid system includes heat recovery and gas compression systems, the total equipment costs reach USD 1710/kW–USD 2289/kW. Additional costs (operational, purchase of materials, wages for employees, etc.) can range from USD 787/kW (1000 kW) to USD 1611/kW (30 kW) [9,36].

For systems with SOFCs, the main costs are for equipment, fuel, and infrastructure. These factors are considered as the main barriers to the implementation of SOFC systems.

According to the calculations of the authors [20], the cost of a planar SOFC with a power of 100 kW was USD 2275/kW. This cost includes the following specific costs: USD 723.45/kW for the stack; USD 154.4/kW for fuel and air supply components; USD 122.8/kW for fuel processing components; USD 316/kW for heat recovery components;

USD 794/kW for power electronic, control, and instrumentation components; and USD 166/kW for assembly activities of components and additional works. However, owing to lower values of current density and additional stack costs for pressurized operations, in hybrid systems the cost of the SOFC stack could be close to USD 3000/kW. Moreover, appropriate considerations should be made for raw material and fuel costs of the hybrid SOFC system.

A hybrid system with SOFC/GT is a continuously operating system and has a complex structure. Therefore, production failures can occur due to equipment failures, which affect the supply of electricity to consumers [28].

A number of technological difficulties are associated with the fact that gas turbines in hybrid systems are not optimized for a connection with an SOFC. For example, at a thermal power plant, it is technologically difficult to combine the operation of a gas turbine and a fuel cell stack. Adaptation of a gas turbine for use in conjunction with a fuel cell is limited by the size of the stack and the direction of heat flows in the SOFC [37].

Long-term stability is one of the main requirements for fuel cells and the degradation of fuel cells limits the industrial use of hybrid installations [38]; for stationary power plants, at least 40,000 operation hours are required, combined with an allowed power loss of less than 10% [39]. Degradation is considered as an increase in ohmic resistance depending on the following operating parameters: current density, fuel use, and temperature.

The problems of equipment layout, the chemical composition of the fuel used, the need to maintain a stable amount of hydrogen in the anode compartment, and the slow kinetics of electrochemical reactions remain unresolved [10]. The development of an integrated control system for the entire hybrid electrochemical–mechanical installation [40], together with monitoring and diagnostic systems, should be based on innovative solutions. Simple PID controllers can be inefficient and the following solutions are possible: feedforward approach, model predictive control, h-infinity, or other innovative control solutions [41,42].

5. Comparison Results of the Combined Heat and Power Systems with SOFCs

Combined-cycle power plants a couple of years ago were one of the most promising energy conversion technologies. They have high electrical efficiency of 55–60% and consume significantly less water per unit of electricity generated compared to steam turbine plants. Currently, combined heat and power systems with a solid oxide fuel cell and a gas turbine are being considered as an alternative. The main feature of an SOFC is operation at high temperatures and high efficiency, regardless the size of the system, and environmental friendliness of energy production. SOFCs are especially attractive for integration into hybrid cycles, increasing their theoretical efficiency up to 70–75%. Effective hybrid SOFC systems have been studied and developed during the past decades. Occasionally, SOFCs were designed to operate with a gas turbine within an integrated system, considering almost all possible layouts of an SOFC/GT system.

Despite the limited number of pilot SOFC/GT hybrid systems, the issues of theoretical analysis, layout, and control of hybrid plants are quite extensively presented in the scientific literature. The results of mathematical modeling demonstrate the possibility of creating efficient and controllable hybrid systems with SOFC/GT, which are also resistant to various factors (fuel composition, changing operating modes, multistage cycles, etc.). However, the difficulties of industrial implementation of hybrid systems are still present; therefore, additional research and development of integrated hybrid system control and operation methods are required.

Most SOFC/GT experimental pilot plants are based on a sealed configuration. Such a layout improves conversion efficiency and reduces capital costs despite much more complex and limited operational management. In SOFC/GT systems operating at atmospheric pressure, the cycles of the two units are not interconnected, which makes it possible to simplify control and operation.

The fuel processing subsystem is of great importance in SOFC/GT system design. The advantage of high-temperature SOFCs is the ability to use natural gas as a fuel, as it

is cheaper and easier to control than the hydrogen used in low-temperature fuel cells. In SOFCs, natural gas is processed into hydrogen using steam reforming, just as it is produced for industrial purposes. Therefore, to solve the problems of fuel reforming in SOFCs, it is necessary to use the accumulated experience and knowledge about the process of industrial steam reforming of methane.

The control of SOFC/GT hybrid systems is a major challenge. The overall efficiency of a pressurized SOFC/GT system is significantly affected by turbine operating limitations. There is also a significant decrease in efficiency when the GT is operated at partial loads. In the case of SOFC/GT hybrid systems operating at atmospheric pressure, performance at partial loads is easier to control due to the lack of communication between the SOFC and GT subsystems.

In all scientific studies under consideration, hybrid power plants show excellent efficiency. However, the economic viability is strongly affected by the high cost of SOFCs. In fact, despite the successful research efforts of the last decades, SOFCs are still far from real commercial availability. The cost of high-temperature SOFCs is still much higher than the cost of gas turbines, piston engines, and alternative fuel cells (low-temperature fuel cells).

Generalized information about the existing technological schemes of combined heat and power systems with solid oxide fuel cells, their features, layout, operating conditions, and efficiency, is presented in Table 1.

Table 1. Features of the combined heat and power systems with SOFCs.

	SOFC	SOFC/GT	SOFC/GT/ST
Features	- Quick response to load changes; - Uncomplicated sealing between fuel and oxidizer flows; - Low capital costs; - Small dimensions; - Simplicity of the production process	- High electrical efficiency; - Complexity of process control; - High cost; - Flexibility of the system	- At a high temperature of the exhaust gases, the greatest efficiency is achieved; - High capital costs; - Complexity of the system; - Suitable for high capacities; - System is inertial
Capacity	From W to MW power class	Pilot plants of only KW power class	Analysis or simulation models only
Electrical efficiency	Up to 55%	Up to 65%	Up to 75%
Application area	- Distributed generation; - Objects of social infrastructure; - Individual heat and power supply of residential buildings	- Thermal power plants	- Thermal power plants
Economical aspects	USD 2000/kW	USD 3000/kW	USD 4500/kW
Reference	aus Bamberg, 2016 [23] Hosseini, 2013 [43] Becker, 2012 [44] Zink, 2007 [45] Homel, 2010 [46]	Cheddie, 2011 [27] Leal, 2019 [47] Li, 2022 [48] Guo, 2020 [49] Hedberg, 2020 [50] Mehrpooya, 2014 [51] Leucht, 2011 [52] Pirkandi, 2017 [53] Facchinetti, 2014 [54] Wongchanapai, 2013 [55]	Pirkandi, 2020 [56] Choi, 2014 [57] Rokni, 2010 [58] Rokni, 2016 [59] Ehyaei, 2019 [60]

6. Discussion of Current Problems and Future Prospects of Combined Heat and Power Systems with a Solid Oxide Fuel Cell

The analysis of literature data on experimental layout design solutions and general operation scheme of combined heat and power systems with a solid oxide fuel cell (SOFC) and a gas turbine was carried out. The scientific papers and studies present quite extensive

data on the design, layout, theoretical studies, and numerical modeling of hybrid power plants. Hybrid systems with SOFCs are proposed to be used as combined heat and power systems for distributed generation systems, for power supply of social facilities, individual heat and power supply of residential buildings, and in auxiliary systems of thermal power plants.

Hybrid power plant projects are presented by such large industrial companies as Rolls-Royce Fuel Cell Systems, Mitsubishi Heavy Industries, Siemens Westinghouse, etc. In several experimental studies, the efficiency of hybrid SOFC/GT systems was lower than expected, at about 50–55% instead of the expected 60–65%. This fact was explained by the imbalance between SOFC and GT subsystems. A more detailed study of the system layout is recommended to achieve the performance targets reported in the theoretical studies. Unfortunately, experimental studies are limited by the cost of installations, together with the rather high cost of system simulation.

The main aspects on which the efforts of researchers should be focused when designing hybrid power plants include:

- Improvement of the hybrid system layout;
- Improvement of the fuel-reforming subsystem;
- Selection of the optimal reforming method and heat source for the reforming process;
- Modernization of SOFC design and selection of their quantity;
- Selection of power installations and their integration into cogeneration or trigeneration cycles;
- Selection of flow direction within the hybrid system;
- Selection of the optimal pressure and ensuring tightness in the hybrid system;
- Application of modern nanomaterials in the production of high-temperature SOFCs.

7. Conclusions

This review provides up-to-date information on several fundamental and applied issues of hybrid energy systems layout and operation. The directions for further technology development and some problems and challenges were also considered. The authors believe that SOFC/GT hybrid technologies will find application in the energy sector and for power supply in the housing and communal sectors. Hybrid power plants are a promising alternative for power generation, especially considering the pace of hydrogen energy development.

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Nomenclature

SOFC	solid oxide fuel cell
GT	gas turbine
MGT	microgas turbine
LNG	liquid natural gas
TPPs	thermal power plants
AC	alternating current
NO _x	nitrogen oxide
ST	steam turbine
CHP	combined heat and power plant

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