ENERGETICS

DOI 10.51582/interconf.7-8.06.2021.032

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PRELIMINARY SUBSTANTIATION OF ADVANCED DIRECTIONS OF MODERNIZATION OF COAL-FIRED POWER PLANTS TO IMPROVE EFFICIENCY

Abstract. The article considers issues related to the modernization of coal-fired power technologies. To increase the efficiency of energy resources, operational reliability, loss reduction and environmental safety the possibilities of trigeneration are considered with application of fuel cells, hydrogen technologies and RE-components that are expedient to use for additional electric energy production. The possibilities of innovative energy components to integrate them into traditional power generation systems are shown, technological schemes are given.

Keywords: energy, coal-fired thermal power plant, efficiency, modernization, cogeneration, trigeneration, fuel cell, hydrogen technology.

Principles of evaluation of efficiency of coal-fired CHPP modernization projects. Prospective directions of coal-fired CHP development are aimed at formation of economically and ecologically acceptable fuel and energy balances and consist of the following: strengthening of energy saving policy; radical reconstruction of heat and electric power facilities of coal-fired CHP based on perfect energy efficient and environmentally safe components; expertise of investment, innovation and other coal-fired CHP projects.

Development of generating capacities. Modern integrated power generation system, for example, with a central power plant of the CHP type, has already become the standard of the new generation energy of technologically developed countries.
Improving the energy efficiency of an electric generating facility, using CHPP as an example, can be achieved by increasing the specific supply of electric power through consistent optimization of plant equipment.

The basic principles of evaluating the effectiveness of projects are as follows: 1) the organization is considered as a profit center, and 2) the account of the increase in cash flow from the implementation of the investment project is calculated as the difference of values with and without the implementation of the project.

This is necessary to assess the effectiveness of commercial investment projects in the development of business plans, feasibility studies and other documents that require evaluation of the effectiveness of commercial investment projects, which lead to economic effect: to obtain additional income, to reduce costs, to avoid costs or to avoid reducing income.

The actual variant of cogeneration plant operation for the last full year is taken as the base case. When calculating the project efficiency, all investment costs associated with the project implementation, including investments in energy infrastructure facilities, should be taken into account. The calculation of the project efficiency should be based on the comparison of the proposed variant of the investment project implementation with the best of the possible alternatives.

**Design recommendations to improve energy efficiency and environmental safety of coal-fired CHPP.** Determination of the list of measures recommended for implementation to improve energy efficiency and environmental safety is carried out according to the results of the energy and environmental survey - audit. The measures recommended for implementation are divided into two categories: organizational and technical measures and investment measures.

Organizational and technical measures in the vast majority of cases are aimed at: strict compliance with nominal operating modes; ensuring the optimal level of loading of units; timely performance of adjustment and repair and restoration work; improving production culture; establishing proper order in energy management.

Investment measures are aimed at: introduction of modern energy-efficient equipment; modernization of processes and technologies; replacement of obsolete production facilities, etc..
It should also be noted that the given sample list of typical measures to improve energy efficiency and environmental safety can be expanded with other typical measures, some of which are listed below.

Use of low-potential waste heat of energy sources for the purposes of industrial zones adjacent to the TPP. Deep heat utilization of flue gases of boiler plants with the installation of automation systems. Reconstruction of water treatment facilities of heat sources, modernization of heat exchangers. Use of mixed fuels at power sources of different capacities. Using the energy of water, wind, earth, solar energy.

Achieved in the mentioned high-temperature solar thermal technologies the temperature parameters are more than (370...550) degrees Celsius and are quite sufficiently effective and environmentally safe.

Decommissioning of morally and physically obsolete equipment with low steam parameters of coal-fired TPPs, its replacement with new plants using effective environmentally friendly coal technologies, modernization and reconstruction of existing condensing and heating units in order to improve their energy efficiency. Application of modular single-shaft CCGT-TPPs with capacity of 40-100-170 MW and GTU-TPPs for consistent reduction of boiler houses and transition to cogeneration of electricity and heat in large cities and municipalities. Application of heat pumps and renewable sources of low-potential heat in heat supply systems (trigeneration).

Increase in electric and thermal power generation in a combined cycle. Reduction of energy carrier costs for CH sources.

Shown power characteristics depending on the time of day, which can be distinguished in several different typical modes: with the base load by fuel; with the base load combined with the use of solar energy; with the base load combined with auxiliary boiler and solar energy; with solar energy and auxiliary boiler.

In addition, the use of other, non-traditional, alternative technical solutions may be recommended, for example, as briefly shown below.

Namely: use of heat of formation waters and geothermal sources for heating and hot water supply (DHW); use of solar collectors for additional hot water and heating of buildings, as well as own needs (SN) of CHP; creation of seasonal and
daily heat accumulation system; use of efficient heat exchangers for utilization of low-potential heat; use of heat pumps for heating and DHW with extraction of low-potential heat from: sewage and industrial water discharges; heat of the basement of buildings; heat of solar collectors; warm exhaust of exhaust ventilation; return heating system network water; water of open water bodies.

Project recommendations on the use of traditional and advanced innovative cogeneration and trigeneration technologies for coal-fired CHP. The Republic of Kazakhstan in the terminology of the International Energy Commission (IEC) belongs to the group of developing countries. Having very significant natural resources, Kazakhstan, at the same time, is characterized by extremely inefficient technologies in all sectors of the economy without exception. This creates significant difficulties in the production of competitive products and, accordingly, impedes the progress of the welfare of the country's population.

The adopted state programs of economic development of the country and the formed list of priority directions of technological development of the regions legally establish limits of reduction of specific energy consumption until 2030 and in the future.

The peculiarity of formation of industrial energy resources in Kazakhstan is that more than 80% of electric energy is generated by thermal power plants. Thermal energy is also produced by industrial heat generating plants of medium and small capacity. In the technological process they use mostly high-ash power coals from the Ekibastuz deposit. These features, combined with the inevitably obsolete power equipment and technologies, mainly of the last century, create an urgent need for modernization of energy facilities in order to significantly reduce energy losses and to bring specific energy consumption in the foreseeable future to the levels of technologically developed countries. Only if this is accomplished can we expect competitive development of the economy.

Thus, effective and sustainable energy supply requires modern both electric and thermal power systems that implement new world-class principles and technologies.

Therefore, for effective and sustainable energy supply in the new modern technological status it is necessary to perform a number of studies and evaluations.
These include: research and assessment of the state and trends of development of thermal energy systems of countries-technological leaders; the state of coal-fired thermal power plants of Kazakhstan. Assess the diversity of possible best energy-efficient heat technologies and global energy trends for the processes of "generation-transmission-distribution-utilization" of thermal energy in Kazakhstan.

Such world energy trends for improving energy efficiency and environmental sustainability are: RES components and technologies in coal-fired CHP modernization systems; creation of distributed and autonomous RES-, SMART- and "H&C"-technology components of coal-fired CHP; modern cogeneration and trigeneration technologies. These and other scientific and high-tech solutions, including combined solutions, should find full application in the creation or deep modernization of coal-fired CHPPs of Kazakhstan.

Combined heat stations are characterized by the fact that the maximum temperature of steam in the energy cycle does not exceed 600 °C, although the temperature during combustion of pulverized coal is about 1300 °C. That is, there is a large thermal irreversibility and reduced availability of full energy use due to the heat transfer from the flue gases to the steam through such a significant temperature difference. Combined heat and power plants can have the following configurations: gas turbine-steam power plant (GT-SPP); MHD-steam power plant; thermionic-steam power plant; combined heat and power plant (CHPP).

Due to the extremely underdeveloped market of own energy technologies that meet the requirements of today and the medium term, we will focus on both successfully proven in industrial operation technical and scientific achievements of technologically developed countries with the potential possibility of adapted transfer, and on promising research and development, which can become potential objects of medium-term modernization and creation of new industrial technologies.

Let us give an example of successful modernization of thermal energy facilities combined scientific and technological solutions that serve to improve energy efficiency and create an increase in generalized estimates of technical and economic benefits in the field of thermal energy generation by cogeneration and trigeneration technologies.
Proposed for consideration of potential transfer the mentioned technologies of cogeneration and trigeneration allow in preliminary estimates to achieve the following results: reduction of energy costs up to 70%; the efficiency of transformation and use of energy may reach up to 93% at place of production of electricity using natural gas; net payback period of the project may usually be from 2 to 5 years; additional savings of 10% to 20% due to heat recovery from existing flows of exhaust gases.

As one of the possible options under consideration for the transfer of energy efficient thermal cogeneration technologies are solutions provided in fully integrated heat recovery projects and which declare maximum heat and energy recovery. This is not a simple and trivial task for the vast majority of industrial power plants, both modernized and newly created, but they can demonstrate unique capabilities, both in terms of all the individual characteristics of the customer and the importance of optimizing customer requirements for the project. The optimization of electrical equipment operation and thermal balancing as a first priority, make cogeneration project solutions more efficient, economical and profitable. This meets the further requirements of an energy- and resource-saving project, maximizing energy utilization with the best possible profitability.

In the technology of conventional cogeneration useful use of energy is in the range of 65 ... 75%, and the possibility of additional increase from unused energy waste is in the range of 18 ... 28%. By applying specially designed scientific and technical solutions the efficiency of energy resources utilization is significantly increased and can reach values from 85% to 93%.

The commercial benefits of cogeneration by the most advanced technologies can provide up to 70% savings in electricity costs, and an additional 10% to 20% savings in natural gas energy in heat utilization up to 90% of the losses from the existing exhaust heat flows. The net payback on projects, according to equipment manufacturers, is usually about 5 years.

**Trigeneration solutions.** Trigeneration systems involve the production and use of heat, electricity and cold from a single fuel source. The simultaneous use of energy allows to obtain a higher level of overall energy efficiency, reduce emissions,
increase the reliability of energy supply and contribute to the reduction of specific investments.

The field of implementation of trigeneration is wide enough and mainly focused on the following technologies of additional energy production: fuel cells, microturbines, Stirling engines, small wind turbines and photovoltaic installations. The various subsystems that make up these energy-generating systems, as well as their most important characteristics and applications, are reviewed. There is an increasing introduction of various technologies allowing the effective use of waste heat from coal-fired TPPs for generating additional electric power. This involves increasing the overall efficiency of the systems and reducing the cost of their implementation. If the technological process requires cooling below ambient temperature (cold air, cold water or ice,) and cooling is performed from the same energy source, such generation process is called trigeneration. Trigeneration provides a number of the most relevant advantages: an increase in the equivalent electrical efficiency of the cogeneration plant due to better use of waste heat; smooth operation of the plant throughout the year, since an increase in cooling demand often coincides with a decrease in heating demand; improvement of environmental conditions through the use of natural refrigerants. Modernization of thermal power facilities according to this principle can potentially realize efficiency parameters in the range of 85-93%.

As noted earlier, one of the indicators of success of creating new energy technologies for modernization of coal-fired TPPs is the long-term successful use of cogeneration and trigeneration technologies in the range of capacities from 400 to 5000 kW, which ensures their full applicability in coal-fired TPPs.

When transferring new energy technologies with their further adaptation to the realities of Kazakhstan it's necessary to fully use significant experience and high level of professionalism in assessing the energy efficiency of technological installations and energy processes and developing innovative solutions for energy-saving technologies, primarily related to cogeneration and trigeneration.

As one example, the FLU-ACE® technology is one such highly efficient option. It can recover up to 90% of the heat at temperatures ranging from 50°C to
70°C, depending on the humidity of the exhaust stream. Detailed features of FLU-ACE technologies are not discussed in this paper, however, according to the developers, the effect can amount to an annual reduction of fuel consumption by more than 15%. Thus, the innovative technologies of trigeneration and cogeneration lead to very significant results.

**Design recommendations on the application of innovative trigeneration technologies for coal-fired CHP plants based on fuel cells.** One of the technologies that has the best characteristics for integration into the trigeneration system is a fuel cell. Systems based on this technology continuously and directly convert the energy of the chemical reaction of natural fossil fuels into electrical energy, heat and water. The modular design, low noise and low emission levels, flexible operation and high efficiency, relatively independent of load, means that these devices are very versatile.

Fuel cells are classified mainly according to two aspects: the type of electrolyte used and the operating temperature. In this regard, we distinguish technologies of both high-temperature fuel cell MCFC and SOFC, with temperatures ranging from 60°C to 1050°C, and low-temperature fuel cell PEMFC, DMFC, AFC, including the PAFC membrane fuel cell, with temperatures ranging from 60°C to 250°C.

Low-temperature fuel cell systems are air- or liquid-cooled. In addition, using a coolant, it is easier to transfer thermal energy in the cogeneration process, both for space heating and water heating.

In high-temperature fuel cell systems such as MCFC and SOFC, the thermal energy of the exhaust gases can be used to preheat the incoming process air. In addition, electricity can be additionally generated by gas-fired microturbines forming a hybrid energy system.

Cold is obtained in the absorption machine, which uses the heat produced in the cogeneration plant. In this case, the heat used in the production of cold can be considered useful under the following conditions. In the production of refrigeration for air conditioning, (5÷7)°C is beneficial: a) all the heat used in simple-action machines, when this heat has a temperature below 120°C; b) all the heat used in double-action machines, when their temperature is below 180°C. In industrial
refrigeration production, for cooling down to -50°C, all the heat consumed in absorption machines when the temperature is below 180°C is useful.

Rationale for the possibilities of innovative trigeneration based on PEMFC fuel cells. The development of fuel cell technology creates great opportunities in the field of power generation. In this system the residual heat allows to have hot water with a temperature that normally ranges between 80°C. This temperature is sufficient to run absorption cooling cycles. The fuel cell cooling system showed electrical efficiency results of 42.27% and thermal efficiency of 44.21%. Thus, the total combined fuel efficiency is 86.48%. Figure 1 shows for example a configuration with SOFC technology considering electrical and thermal energy production. This SOFC scheme by Siemens-Westinghouse has shown an electrical efficiency of 43.3%, thermal efficiency: in heating - 43.7%, in cooling - 52.6%, in hot water production - 46.7%. The efficiency results in three operating modes are up to 87.95%, 95.9% and 90%.

Thus, the characteristics in trigeneration processes are considered, which makes it possible to achieve a high level of overall efficiency in the use of coal-fired CHPP fuel through the use of residual heat.

In relation to industrial processes requiring heat, they are classified according to the temperature level of the heat required: low temperature processes, below 100°C; medium temperature processes, 100 to 300°C; high temperature processes, 300 to 700°C.

Thus, the process can be served by any of the different fuel cell technologies - PEMFC, PAFC, MCFC and SOFC. Fuel cells can operate with constant or variable power, depending on load modes. High-temperature fuel cells are more suitable for the first mode of operation, while low-temperature fuel cells are more suitable for the second mode of operation.

Technical justification of application of carbon-free energy carrier technologies for modernization of coal-fired TPPs. General characteristics of hydrogen as a potential carbon-free component for reducing the primary fuel of coal-fired CHP plants. If fossil fuels are converted to H2 and the resulting CO2 is sequestered, an energy carrier is produced that can be utilized without greenhouse
gas emissions. Hydrogen H2 is a versatile energy carrier. It can be utilized either alone or in a mixture with other gaseous fuels. H2 can be used as a fuel in gas turbines. Hydrogen H2 is an ideal fuel for most types of fuel cells, which are highly efficient. Hydrogen H2 can be produced, for example, by electrolysis of water with electricity from wind, sun, other natural renewable sources. Hydrogen technology has been developed and industrialized in the form of modular designs.

![Diagram of SOFC technology application system for heat and electricity generation](image)

**Fig. 1 SOFC technology application system for heat and electricity generation**

**Analysis of available hydrogen production technologies for energy needs.**
Hydrogen technologies are based on various methods of hydrogen production. One of which is water electrolysis - the process of dividing water into chemical components (hydrogen [H2] and oxygen [O2]), thereby converting electrical energy into chemical energy.

The power of individual electrolysers can reach up to 100 MW. Large-scale electrolysers are prerequisites for hydrogen-based electricity storage. Electrolyzer stacks, as shown in Figure 2, that group up to a hundred cells together.

Larger plants are created by adding electrolyzer stacks in parallel, which reduces the total capital cost from 45% for one stack to 35% for 50 stacks. It also increases plant flexibility and reliability.
Electrolysis plant according to the typical scheme in Figure 2 contains parallel connected electrolyzer stacks consisting of cells as shown in Figure 3. The electrolyser is powered from AC mains through AC/DC power converter - power electronic rectifier; water is supplied directly to the electrolyser through the deionizer and is accumulated for temporary storage in a special tank. The main products at the electrolyser outlet are: a highly saturated innovative energy carrier - hydrogen. It is supplied to the consumer - technological facilities for combustion or conversion, including for the CHPP's own needs.

From the electrolyser itself, the hydrogen generated in the electrolyser is pumped through a dehydration unit and via an auxiliary compressor into a special tank for temporary storage under pressure. The by-products of the electrolysis process in this case are the oxygen generated as well as the thermal energy released. Both the main product and the by-products of the electrolysis can be used with positive effect in the coal-fired thermal power plants under consideration. To date, the following basic types of electrolysers have been developed by electrolyte type and by degree of technical maturity: alkaline, proton exchange membrane [PEM] and solid oxide electrolyzer cell [SOEC].

**Alkaline** - remains commercially the most common option for systems over 200 kW. Has limited potential for possible cost savings. The proton exchange membrane PEM is a promising alternative to alkaline technology. It is highly flexible, easier to handle pressurized hydrogen feeds, and has a simple design, creating significant potential for cost reduction.
The SOEC solid oxide electrolyzer cell can produce a simultaneous process - co-electrolyzing water and CO2 to produce syngas (hydrogen H2 and carbon monoxide CO) and oxygen with very high efficiency. SOEC can also be used in electrolyzers or fuel cells. It is potentially cheap to produce.

Over the past decade, significant improvements have been made in electrolyzer efficiency; under nominal conditions, PEM and Alkaline can now achieve 78% efficiency.

In terms of cell layout, PEM and SOEC cells are simple in design, compact, and built around a solid membrane with no moving parts. Alkaline cells, on the other hand, are made of cheaper materials, but have a much larger mass-dimensional cell area and a more complex electrolyte circulation loop. In terms of electrochemical performance, REM electrolyzers are more compact and potentially cheaper to manufacture; the smaller mass-size cell area contributes more to lower production costs per unit output. SOEC electrolysers have the most promising thermodynamic potential. Proton exchange membrane PEM requires a more thorough feasibility study of competitiveness in megawatt-scale design applications.

**PEM status and prospects.** PEM electrolyzers have more than 20 years of experience. The 1 MW PEM electrolyzer stacks are already in successful commercial operation; they will be 30 times smaller in mass and size and much more flexible with respect to load regimes than their alkaline counterparts. The multi-MW PEM units provide efficient load power control with a ramp rate of 30 MW/s and a "black start" in less than ten minutes.
Advantages: simple design and reliability, no moving parts, lightweight, compact, modular power ramp-up principle; compact system; efficiency similar to alkaline, but with higher current density; very fast response time; high operating pressure; high potential for lower investment costs by implementing the modular principle.

The proton exchange membrane, as an example for hydrogen gas production, has the following parameters. Working pressure potentially up to 300 bar, working temperature - 60...80°C with the prospect of 130...180°C; flexibility of technological modes is high, the minimum possible working load - 0%; reactivity - from stopped state to full load - not more than 10 sec, for the best results - about 1 sec; "black start" time - not more than 10 minutes; hydrogen gas purity - 99.9%; system commercial efficiency - 77%, potential - 84% at 1.0A/cm²; maximum stack size (power) - 100 kW(chem) with 500 sq. cm and 1 MW(el) stack under construction; largest operating 1 MW(el) plant of hundreds of stacks.

The solid oxide electrolyzer SOEC cell is a revolutionary technology that can jointly electrolyze water and CO₂ carbon dioxide to produce syngas for synthetic fuel generation with very high energy efficiency.

SOEC cells can also be used in reverse mode as a fuel cell for electricity generation, minimizing the investment costs of hydrogen-based generation-consumption balancing systems. SOEC cells are likely to be used in a joint electrolysis mode rather than solely for the production of energy hydrogen.

Operating temperature range - within 700...900°C. Efficiency - more than 89% in the current period of development with potential possibility of reaching 98% of operational efficiency.

Benefits. Highest energy efficiency, reaching nearly 100% at stack level. Low capital costs: high density and no noble metals. Possibility of co-electrolysis of CO₂ and/or H₂O to produce syngas (H₂+CO). Reversible use as a fuel cell with the possibility of synergistic thermal energy recirculation.

Unlike other cells, SOECs work best at high temperatures. Thus, much of the energy required can be provided in the form of thermal energy (heat) instead of electricity, increasing energy efficiency by almost 100%. SOECs can also
electrolyze both H2O water and CO2 carbon dioxide to produce a mixture of hydrogen H2 and carbon monoxide CO, called "syngas," which can be further processed into synthetic fuel. Another advantage of SOECs is that SOECs can be used both as electrolysers and as fuel cells, creating new technological opportunities to store electricity efficiently and inexpensively in both directions.

In the last decade, there has been renewed interest in electrolysers using RES technologies to generate electricity.

**Solid oxide** electrolyzer cells [SOEC], high temperature - 800°C Energy conversion efficiency approaching 100% at stack level and 90% at system level at current densities up to 1A/cm2. Specific energy-to-hydrogen conversion efficiencies can be as high as 100% at the system level.

The priority is to further reduce investment costs per unit of installed capacity. It is assumed that modern electrolysers use surplus electricity from low-cost RES, which implies a relatively limited number of operating hours per year. At low utilization rates, investment costs become a more important factor than efficiency.

There are two main opportunities to reduce the capital costs of electrolysers: i) lower production costs per unit cell area and ii) higher current densities.

The effect of electricity price and capital investment depends on the utilization or annual load factor of the electrolyzer plant. If the electrolyzer is only used less than 20% of the time, the most important component becomes the investment cost. When utilization rates range from 20% to 90%, both capital costs and efficiency have the most significant impact on project economics.

Fuel cells and "combustion turbines" can be used for extended use of hydrogen technology as a tool to reduce the consumption of primary fuel at coal-fired thermal power plants like CHP plants. In doing so, thermal energy losses can be recycled in two ways: (1) for heating purposes, as part of the application in the combined heat and power production - CHP plants. It should be noted, however, that heat is very difficult to transport efficiently over long distances, so micro-CHP systems for decentralized applications are a very important part of modern fuel cell systems. The energy efficiency of hydrogen-fueled CHP systems should be as high as 75%; and (2) converted to electricity in a combined cycle power plant to improve electrical
efficiency in continuous operation. High-temperature waste heat combined with a large-scale power system is needed to offset the increase in capital costs, limiting the application to gas turbines or high-temperature fuel cells. Fuel cells and combustion turbines have areas of best use and do not compete directly for the same application. Namely: a) Fuel cells give priority to reliability, autonomy and low maintenance requirements in operation. A typical example would be standby power supply systems, uninterruptible power supply systems, in which the most important factor is the reliability and continuity of energy supply. The value of specific capital costs in this case is not critical; and b) Hydrogen H2 turbines will be stationary and capacity of at least 10 MW, due to the reduction of specific costs by increasing the unit capacity. This is positive compared to high-modulus fuel cells.

Fuel cells are grouped into low-temperature and high-temperature categories. Low-temperature fuel cells. The most promising is the proton exchange membrane [PEM]. The PEM fuel cell has always been the most produced type of fuel cell. It is also suitable for stationary applications and is a popular choice for grid management services because of its reactivity. High-temperature fuel cells are generally more efficient (up to 50%) and well-suited for stationary megawatt-scale cogeneration plants. They are commercially available with a decent lifetime (unlike high-temperature electrolysers), but remain quite expensive to produce. Solid oxide fuel cells are especially promising because they can easily be converted to electrolysers and can be operated using H2, syngas, methane, or methanol.

Gas turbines can also be used to burn hydrogen as a fuel gas. Flexible gas turbines can handle an undifferentiated mixture of H2 and CO with hydrogen content up to 70% by weight. They are commercialized for coal gasification power plants.

Stored hydrogen can be used to generate heat or electricity in a combined heat and power plant using fuel cells or gas turbines.

Hydrogen, which is essentially fuel gas, can also be used in combustion turbines. When hydrogen and oxygen are burned, water and heat are produced. The heated steam is fed into the turbine to produce mechanical energy, which in turn is converted into electricity by the generator. According to estimates of turbine manufacturers, mixing 1-5% in volume will not require any design changes.
Fuel cells and combustion turbines do not compete in the same applications. Fuel cells are much more suitable for decentralized, distributed applications. An example of this for an innovative, modernized coal-fired CHP plant could be the supply of hydrogen fuel for the vehicle fleet, which serves the CHP plant's own production and administrative and social infrastructure and whose maintenance costs are part of the overall plant costs. Thus, due to the reduction of indirect costs, the overall useful commercial benefit in the production of the main products of CHPP increases. This, naturally, contributes to the reduction of costs of the main energy carrier - coal for own needs of CHPP.

Combustion turbines are more suitable for large-scale centralized requirements of stationary power facilities and must have significant megawatt-class capacities to produce a tangible investment effect.

Specifically, efficiencies are: about 30% for low-temperature fuel cells; about 45% for hydrogen H2 turbines operating in an open cycle; about 50% for high-temperature fuel cells, particularly solid oxide fuel cells [SOFCs]; and up to 60% for H2 turbines operating in a combined cycle, where the hot exhaust vapor from a gas turbine is reused to drive a steam turbine, increasing efficiency through flexibility with respect to the current load schedule. The efficiency of the H2 turbine is slightly higher than that of the gas turbine.

Figure 4 shows the main ways of conversion of chemical energy of used hydrogen for its application at coal-fired innovative CHP with application of hydrogen turbines or fuel cells. Fuel cells provide a direct, direct conversion of chemical energy of hydrogen into electric and thermal energy, which can be successfully used either directly for MOS CHP or will be an additional commercial product additionally produced by this CHP.

Hydrogen turbines, in their turn, provide conversion of chemical energy of hydrogen energy resource through sequential conversion of hydrogen chemical energy into thermal energy in hydrogen turbine, then probranching of thermal energy into mechanical energy of turbine (and generator) rotation, finally, final stage of conversion of mechanical energy into electrical (and thermal) energy, which has further useful application either in MSH CHP or as additional commercial
Fig. 4 Possible ways of energy conversion at coal-fired innovative CHP using hydrogen turbines and fuel cells

Depending on fuel cell and turbine technologies, reuse of waste heat can increase hydrogen energy efficiency (heat and power) by up to 76% today (and up to 80% in the near future). The corresponding highest CHP efficiency with H2 hydrogen is 56% with a projection of up to 65%. Heat recirculation is necessary to improve the energy efficiency of stationary fuel cells and turbine H2 units.

Conversion of energy into electricity in a steam turbine. Combining a fuel cell or combustion turbine with a steam turbine creates a combined cycle power plant. To drive a steam turbine with sufficient efficiency, these plants require higher quality thermal waste with temperatures above 500°C. They must also be large systems, since scaling up the steam turbine capacity provides important economic benefits and efficiencies. The combined energy cycle and conventional CHP technologies can be used together. In addition, there are currently no significant technical barriers to the joint application of these technologies to hydrogen fuel cells or turbines. The fuel cell is only a small part of the plant, both in terms of cost and size. In the last few years, stationary equipment for standby power supply systems has been increasingly used, including for the own needs of coal-fired thermal power plants.

Hydrogen fuel cells for own needs of coal-fired thermal power plants. The fuel cell system that can be used for a stationary power system, for example, coal-fired CHPP can be represented as a scheme in Figure 5.
Electric power in the available for the majority of industrial consumers, e.g. belonging to FC fuel cell installation consists of stacks of fuel cells connected in series, plus the balance of the installation consisting of pumps, compressors, power converters, cooling circuits and other necessary components.

The input energy of the fuel cell is the chemical energy of hydrogen and oxygen. Both components are pumped with the necessary parameters using hydrogen and oxygen compressors. The output parameters of the innovative device are: electrical energy, thermal energy and water.

Electric power in the available to most industrial consumers, such as those belonging to the group of consumers of own needs of the infrastructure components of CHP, including those described above, is provided by the use of a DC/AC power converter. This is a power electronic fully controllable device with possibility of deep regulation of output current, output voltage and, accordingly, output power, depending on requirements of load parameters of any auxiliary components of cogeneration plant. This inverter can operate as an autonomous inverter - in the mode of load control, if there is no direct connection to the external electric network, or can operate in the mode of inverter controlled by the network - inverter, slave to the network. SOFC operate at high temperatures, increasing fuel and electrical efficiency.
Comparative advantages: the highest efficiency among fuel cells; suitable for CHP and combined cycle power; no noble metal catalyst; fuel flexibility; good fuel impurity tolerance; simple system; easy reversibility into electrolyzer. SOEFC fuel accepts not only H2, but also any light hydrocarbons (e.g. methane, propane), CO or methanol as a feedstock. Due to their technical characteristics SOFCs are mainly suitable for large-scale stationary plants or for decentralized CHP plants.

**Gas and hydrogen turbines for modernization of coal-fired thermal generation.** Gas turbines can be a good alternative to fuel cells for large-scale stationary applications. Minor technical modifications will be required to operate gas turbines using methane or hydrogen, or mixtures such as hydrogen-enriched natural gas [HENG] (CH4+H2) or syngas (H2+CO). Flexible-fuel turbines are already commercially available for use in coal-fired gasification power plants, where the hydrogen content of the mass can vary up to 50%.

**Energy production from fossil fuels with carbon dioxide capture.** Carbon capture and storage has recently gained increasing interest in the thermal energy industry, mainly as an option to reduce CO2 emissions. If CO2 is captured in the flue gases during combustion and does not enter the atmosphere, it will not contribute to the greenhouse effect. An alternative is to replace the combustion air in the power generation process with pure O2 mixed with recirculated flue gases. This produces a flue gas consisting only of CO2 and H2O, and the cooling and condensation is sufficient to produce virtually pure CO2. This can provide almost 100% CO2 capture.

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