Hybridization and the combination of technological solutions in small distributed energy

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Abstract. In the article an exergy analysis of technological schemes of mini thermal power plants with technologies of hybridization and combination was carried out. The first technology deals with a low-power hybrid station that uses both traditional fuel (natural gas) and renewable energy sources (solar energy). The second technology deals with the combined production of energy (thermal and electrical) and by-products - activated carbon, sulfur, ash and slag materials. The values of the exergy efficiency of the considered schemes are obtained. It was concluded that the use of hybridization and combination technologies allows to increase the exergy efficiency in comparison with the typical scheme for obtaining energy at distributed energy objects.

1. Introduction and the purpose of research

The current trends in energy development dictate the need to increase the requirements for reliability and quality of power supply to consumers. In this aspect technologies of small distributed energy which based on the modern solutions are one of the key mechanisms for achieving these indicators. In the world practice at present time in addition to distributed generation include demand response, distributed power storage systems; energy efficiency management; microgrids; electric vehicles [1].

The most common is the technology of distributed generation which is a combination of low capacity power plants located directly near the place of energy consumption or distribution network, when there are several consumers. When the price of electricity changes and to reduce consumer costs demand response technology emerges which consists in mutually beneficial regulation of the volumes and modes of electrical consumption. Technology energy efficiency management implies a set of actions on the consumer side, which contribute to reducing its energy needs. The microgrids is a power system that consists of distributed energy sources and several electrical loads (consumers) that operate as a single object in parallel with an existing network or in an autonomous mode. Distributed power storage systems are a collection of storage systems that provide the capability for redundancy as well as demand management. In addition, electric vehicles that are a distributed energy resource and perform the functions and consumers of energy and distributed drives also belong to technologies of this type. The proximity to the direct consumer combines all of these listed technologies.

In the article the authors consider the technology of distributed generation in terms of hybridization and combination. Currently the resource base of small distributed energy objects is represented by a
wide range of fossil fuels and industrial wastes [2, 3]. However one of the main criteria for choosing an energy source for a particular object remains the accessibility and availability of the selected fuel in the region. This will reduce transportation costs for fuel delivery, as it is local, and ultimately will reduce the cost of energy produced and thereby reduce consumer costs. At the same time the technologies of using fuel in conditions of small energy must meet the indicators of energy efficiency and environmental friendliness. Therefore the main objective of creating objects of small distributed energy is to increase the efficiency of fuel use while respecting the indicators of technical and economic efficiency and environmental friendliness.

As part of this study the authors selected low-capacity hybrid stations operating on both traditional fuel (natural gas) and renewable energy sources (solar energy) as the object of study. [4]. The solar energy enters the surface of the Earth regardless of the presence of any devices for its use and is estimated at $1.2 \times 10^{17}$ W. Solar energy accounts for more than 99.99% of all renewable energy sources on Earth. This corresponds to an average available power per person in the amount of 15 MW. In order to use at least a small part of this energy it is necessary to apply various methods, including the use of hybrid power plants with gas turbines and a solar air receiver-heater. Similar projects were implemented in Spain - 4.6 MW unit with an SOLUGAS type air solar heater and 11.86 MW with a similar REFOS type receiver-heater [5, 6]. The authors conducted a study of operating parameters of hybrid mini thermal power plants with a gas turbine unit (GTU) with a capacity of 4.6 and 11.86 MW, in which fuel savings are achieved by heating the air after the compressor using solar energy. Economic evaluation of hybrid schemes is also performed, which indicates the feasibility of their implementation [7].

As for the principles of combination, i.e. production energy (electrical and thermal) and by-products, it is necessary to note the following. As known, at the end of the last century, most products of organic chemistry were made from coal. As the volume of oil production increased, there was a gradual displacement of coal fuel from the market. However, with the development of environmentally friendly technologies for the use of solid fuels, and forecasts for a decrease in oil and gas reserves, coal fuels are gaining all the great demand. Moreover, the possibility of obtaining valuable chemical products during the thermal processing of coal, in the conditions of small distributed power facilities, will provide consumers with not only energy, but also highly sought by-products. During thermal processing various valuable chemical raw materials can be obtained from coal. In the [8] the author presented and analyzed the review of the relevant literature on the pyrolysis of coal. During the pyrolysis of coal fuel possible by-products are coke, semi-coke, sorbents, tar, fuel gas; during gasification, synthesis gas, fuel gas, generating gas; during liquefaction: liquid fuel oil, phenols, light hydrocarbons, motor fuels [9]. In other words, when using solid fuel at low-capacity power plants the technology of combining power generation and by-products is provided.

2. The methods and approaches
As a method of mathematical modeling and evaluating the effectiveness of these objects a topological method was chosen. The essence of which is to build material, thermal and exergy flow charts ("graphs"), compose balance equations for material, thermal and exergy flow schemes, solve balance equations using iterative methods [10].

Through structural analysis, interdependencies are established between the elements of the scheme, open and closed sequences of elements are identified, and the sequence of calculations is determined. Then an assessment of the thermal efficiency of the system is carried out with the determination of the coefficient thermal efficiency and the main thermochemical processes of fuel processing and the production of by-products are studied. At the final stage the exergy (thermodynamic) efficiency of the schemes is determined. The thermodynamic efficiency of technological objects small distributed energy can be most fully evaluated with the help of the thermodynamic efficiency of individual devices, units and the entire system as a whole. In this case the most appropriate is the use of the exergy method which determines the exergy of material, heat and energy flows entering and leaving
each element of the scheme. Exergy analysis method is widely used to assess the effectiveness of combined energy production systems, including hybrid stations [11-13].

3. Description of technological schemes
In Figure 1 is a schematic diagram of a hybrid mini thermal power plant. The installation works as follows: the compressed air from the compressor is heated in the receiver to a temperature of 800 °C and fed to the combustion chamber of a Mercury TM 50 turbine modified to operate under the influence of solar energy.

The combination process is described in the following schemes. The scheme of mini thermal power plant with the production of sulfur works as follows (Figure 2). Coal enters the hammer mill, where it is crushed and dried at the same time due to the heat of the drying agent. Then the coal is sent to the gasifier, where, in the presence of water vapor and air (oxidizing agents) is gasified. Generator gas from gasification of coal is fed for cleaning and cooling, and slag is removed. After cooling to 400 °C in the contact heat exchanger, the generator gas enters the purification unit. Purification of solid particles is carried out in two stages - larger particles are trapped in a cyclone, small particles - in a bag filter. Purification of H$_2$S is carried out with activated carbon. According to the process conditions, the generator gas must be cooled to 40 °C before being supplied to the absorber. In the literature describes various methods of purification from H$_2$S [14].

![Figure 1. The schematic diagram of a hybrid mini thermal power plant.](image)

However only those of them that are characterized by the compactness of the equipment used, the ability to regenerate the adsorbent and release sulfur in a chemically pure state can be used for the mini thermal power plants. The purification process consists in the catalytic oxidation of hydrogen sulfide to elemental sulfur by air on the surface of activated carbon [15].
For the reaction to proceed at a sufficient rate at ordinary temperature, ammonia is added to the gas to be purified. The advantage of this method is the high degree of extraction of hydrogen sulfide with the simultaneous release of a part of organic sulfur compounds, as well as the possibility of obtaining high-quality commercial sulfur. The released sulfur clogs the pores of the activated carbon, gradually reducing its activity. Coal is regenerated using ammonium sulphide solution, which releases sulfur from coal pores to form polysulfides. When polysulfides are heated under pressure, elemental sulfur is released, which melts and can be discharged into forms or precipitated as a crystalline precipitate, which is then filtered and washed. The yield of elemental sulfur during coal regeneration reaches 95% of the content in the gas [15]. The purified generator gas enters the combustion chamber of a gas turbine unit, where electrical energy is produced. Waste combustion products after the GTU are sent to the waste-heat boiler to produce thermal energy in the form of steam.

The scheme of a small thermal power plant with the production of activated carbon is shown in Figure 3. By analogy with the previous scheme, after grinding and drying in a hammer mill, coal is fed into a fluidized bed gasifier, where generating gas and slag are formed. After the cleaning system of large and small dust particles, the generator gas is sent to the combustion chamber of the GTU. The production process of the by-product - activated carbon is the following. When fed into the gas generator, the carbon is carbonized as a result of contact with the hot generating gas and sent to the activator, where water vapor is fed in a 1:5 ratio. When activated, the internal surface of the coal increases, a developed pore structure is formed. After cooling to 50 °C, activated carbon can be used as a finished commercial product. Combustion products after GTU are sent to a waste heat boiler.

Figure 2. The scheme of mini thermal power plant with the production of sulfur.

Figure 3. The scheme of mini thermal power plant with the production of activated carbon.
The process of energy production at coal mini thermal power plants with production of ash and slag materials is shown in Figure 4.

![Diagram of mini thermal power plant with ash and slag production](image)

**Figure 4.** The scheme of mini thermal power plant with the production of ash and slag materials.

By analogy with the previous schemes, the coal after the mill is sent to the gasifier. The ash from the gasifier is fed into the installation of pneumatic collection and then into the collection container of ash. The slag coming from the gas generator is cooled in a water bath and fed to the slag dryer. From slag dryers, slag is transported to the mill, where it is ground and mechanically activated, and then fed to the tank. From the tanks, ash and slag enter the humidifier and then granulate in the installation. The finished granules are transported to the tank, from where the loader is fed for packaging and can be sent to consumers and used as a filler for concrete. Generator gas after cleaning and cooling is sent to the combustion chamber of the GTU. Combustion products from GTU are sent to the waste-heat boiler.

4. Results and conclusions

For a hybrid mini thermal power plant in a solar air heater, it is proposed to use the following expression to determine the exergy efficiency:

$$\eta_{eG} = \frac{N_{GTU}}{E_{f}}$$

where $N_{GTU}$ is the electric power generated by the GTU; $E_{f}$ is the exergy of fuel which is calculated as the product of fuel consumption by its calorific value.

In the second scheme coal of the Kizel basin is used as fuel, for the third and fourth Kuznetsky. The main indicators of gasification of solid fuels, such as the composition of the generating gas, its calorific value, the consumption of oxidants - water vapor and air are determined by the generalized method using known dependencies [6].

The exergy efficiency of the mini thermal power plant scheme with the production of sulfur $\eta_{exS}$ is determined by the ratio of the values of the generated electrical power $N_{GTU}$, water vapor exergy generated in the heat recovery boiler $E'_{w,v}$, exergy of the product sulfur $E'_{s}$, exergy of the main processes (generator gas cleaning and combustion in the combustion chamber of a gas turbine unit) $\sum E'_{w}$, water for cooling the generator gas and for generating steam in the recovery boiler $\sum E'_{w,v}$, ammonium sulphide $E'_{(NH_4)_2S}$, activated carbon $E'_{c}$, and the electric power of all devices $\sum L$: 
The exergy efficiency of the mini thermal power plant scheme with the production of activated carbon $\eta_{\text{exAC}}$ is as follows:

$$\eta_{\text{exAC}} = \frac{N_{\text{GTU}} + E_{\text{a,c}}^a + E_{\text{w,v}}^a}{E'_c + \sum E_{\text{air}}' + \sum E'_w + E_{\text{NH}_4}^a + \sum L + \sum E_{\text{w,v}}' + E_{(\text{NH}_4)_2S} + E_{\text{a,c}}'}$$ (3)

where $\sum E_{\text{a,c}}'$ is the exergy produced activated carbon; $\sum E_{\text{w,v}}'$ is the exergy of water vapor going for gasification and activation; the remaining designation by analogy with formula (2).

For the scheme with obtaining of ash and slag materials determination of exergy efficiency $\eta_{\text{exASM}}$ is carried out using the following dependency:

$$\eta_{\text{exASM}} = \frac{N_{\text{GTU}} + E_{\text{ASM}}^a + E_{\text{w,v}}^a}{E'_c + \sum E_{\text{air}}' + \sum E_{\text{w,v}}' + \sum E_{\text{w,v}}'}$$ (4)

where $E_{\text{ASM}}^a$ is the exergy obtained ash and slag materials; $\sum E_{\text{w}}'$ is the water exergy for cooling slag and generating gas; $E_{\text{w,v}}'$ is the exergy of water vapor flowing into the gas generator; the remaining designation by analogy with equations (2) and (3).

For the calculation of individual exergy streams, the previously presented dependencies are used [16]. Table 1 shows the results of the exergy analysis of the considered schemes.

Analysis of the experience of the mini thermal power plant operation shows that the use of these objects is especially important for those regions where the centralized power supply is completely absent and at present time have to use diesel generators working on imported fuel. Objects of small distributed energy should be created mainly not as competitors, but as a natural complement to centralized sources. Since such facilities are as close as possible to the consumer and are often his property, issues of efficiency and ensuring minimum environmental impact come to first plan.

| Type of scheme                                                                 | Exergy efficiency, % |
|--------------------------------------------------------------------------------|----------------------|
| Mini thermal power plant with the receipt of commodity sulfur                  | 25,4                 |
| Mini thermal power plants with the production of activated carbon             | 47                   |
| Mini thermal power plant with the production of ash and slag materials        | 42                   |
| Hybrid mini thermal power plant at an intensity of solar radiation 746 W/m²   | 46,66                |

To improve the efficiency of the mini thermal power plants the use of hybridization and combination methods has been proposed. On hybrid mini thermal power plants that use solar energy, it is possible to increase the exergy efficiency from 34.5 to 46.6% with the maximum intensity of solar radiation due to the preheating of the air after the compressor and significant fuel savings. When combining the production of various products at mini thermal power plants (when using coal as fuel), an increase in exergy efficiency is achieved from 25% to 47% (in the production of activated carbon as a by-product). This approach not only reduces the cost of energy production through the sale of by-products, but also eliminates waste generation, as in the production of sulfur and ash and slag materials.
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