Polygeneration plants in the energy complex of oil and gas enterprises: the concept of synthesis and a method for assessing efficiency

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Abstract. The article proposes a concept for the synthesis of polygeneration plants as part of the energy complex of oil and gas enterprises, which expands the possibilities of inter-industrial integration of energy and technological systems in the direction of creating closed utilization cycles. An example of a complete set of equipment for an installation for the combined generation of energy resources, water and carbon black, utilization of wastewater and low-pressure hydrocarbon gases is given. A two-dimensional model of a multi-criteria efficiency index is proposed for the analysis of performance indicators and the efficiency of integration of polygeneration units with energy technology systems of oil and gas enterprises.

1. Introduction
The development of the energy complex (EC) of oil and gas enterprises (OGE) is carried out in areas focused on the modern stage of innovative changes in the concept of energy resources (ER) generation, in energy technologies and in the structure of energy systems. At the same time, solving the problems of synthesis of energy technology systems (ETS) and polygeneration plants (PP) at OGE’s is complicated by the problem of partial static nature of the energy industry in combination with the dynamics of the parameters and structure of the technological subsystem (TS), diversification of production throughout the life cycle of the enterprise (due to changes in the parameters of hydrocarbon raw materials and products) and the permanence of the development process and introduction of energy and resource saving measures. In addition, the peculiarity of OGE lies in the functional relationships with the Russian fuel and energy complex, in particular, with external energy supply systems (EESS), both in terms of ER and marketable products – natural gas, gas condensate, a wide fraction of light hydrocarbons, a line of motor and energy fuels, liquefied gases and other technological products. Therefore, the concept of PP synthesis as part of the OGE’s must correspond to the strategic prospects for the development of the energy industry in Russia in accordance with global trends [1–3].

The analysis of scientific and technical publications on the issues of energy supply to the OGE showed a steady trend towards an increase in the EC of the share of autonomous energy sources that realize the potential of recovery energy resources (RER) and waste, power plants for their own needs with combined cycle gas turbines (CCGT) and installations using flare gases and renewable natural energy sources (RES) [3–10]. The scale of the use of integrated power supply of individual objects, the use of distributed polygeneration and multi-energy systems is growing [2, 11–15]. The scientific and technical results obtained in these works are adapted mainly for the technological topology of production and transportation of oil, gas and gas condensate feed (OGCF) or for central power plants. At the same time, for OGE requires a comprehensive solution to the problem of creating a PP, which uses the
potential of wastewater and low-pressure hydrocarbon gases (LHG) – field gases in the final period of operation, associated petroleum gases, gas condensate stabilization gases, plant gases of OGE processing profile.

In order to assess the effectiveness of the structural-parametric and design solutions adopted for the PP in the EC of OGE, it is necessary to create a system of multicriteria indicators that make it possible to take into account as much as possible all the influencing factors and variable parameters of various methods of energy generation, wastewater disposal and LHG in conjunction with EESS, water supply systems, water disposal and conditioning waste. At present, technical and economic, energetic, thermodynamic, ecological and combined methods for assessing the effectiveness of complex systems are widely used [14, 16–28]. At the same time, noting the versatility of the thermodynamic method for analyzing the effectiveness of complex polygeneration systems, most authors at the final stage of the study carry out technical and economic calculations with the determination of private or complex indicators.

Summarizing the main provisions of the work on general scientific and methodological issues of the analysis of the EC of OGE’s and energy facilities of various localization, we can conclude: the developed methods for the synthesis of optimal PP must ensure systematic, complexity, universality and consistency in the implementation of technical solutions. In this regard, a multicriteria systematic assessment of the efficiency of the PP as part of the EC of OGE is required with the determination of the potential of its own resources (RER, combustible waste, LHG, effluents) and the development of scenarios for its technical implementation, as well as solutions for the integration of PP with TS and the use of RES.

2. Concept of synthesis the PP for the EC of OGE

Over the past 18 years, the authors have carried out theoretical and experimental studies of the EC of large OGE (mainly on the processing of heterogeneous OGCF of various gas condensate fields) in the dynamics of the development of TS and ETS, systems for the utilization of RER, as well as changing relationships with EESS. The results of a multicriteria analysis of the generation and consumption of ER, fuel, water in TS and EC of the studied objects (systematized in publications of recent years [29–32]) showed that the creation of highly efficient, reliable and environmentally friendly PPs in EC with the requirements of structural-parametric and instrumental maneuverability and efficiency is achieved through the integration of modular technological and energy blocks.

The concept of synthesis of PP is based on the decomposition-search method with the parallel solution of the following basic problems:

- polygeneration of ER – electricity, thermal energy and cold in own sources, including using thermal RER of OGE;
- utilization and / or conditioning of LHG (and combustible hydrocarbon waste) with the production of technological and / or energy products;
- utilization of waste water from TS and EC of OGE with the production of process water for own consumption of TS and EC.

The initial data are the characteristics of the OGE (which are advisable to form on the basis of the energy and technological audit of the facility, taking into account the dynamics of the TS in retrospective and prospect): required parameters of generated and consumed ER and water; fuel potential; parameters of RER, LHG and effluents. The parameters to be determined are: power of modules PP; equipment design parameters; various regime parameters of their functioning and performance indicators in the corresponding periods of time.

The concept of synthesis of PP in the EC of OGE is illustrated by a generalized scheme (Figure 1), which implements the principles of polygeneration and integration of EC with TS. The diagram does not show the flows of ER systems 2.M (coolants and compressed air), which are also generated in PP (3.1...3.L). The flows of ER, water, effluents and LHG (and / or flare gases), marked in Figure 1 by circles, can be completely or partially excluded from the production cycle of OGE. So, for some OGEs (enterprises for processing gas-condensate feed and gas transportation), it is possible to create autonomous EC with PP and ETS, integrated with TS productions. This experience has long been
existing for similar US and Canadian OGEs [33]. In this case, streams III, IV and V from the EESS are replaced by own resources of OGE. For refineries with deep processing of OGCF that have a shortage of fuel gas for energy generation, when synthesizing PP, it is necessary to take into account additional for fuel gas consumption (stream III in Figure 1 cannot be excluded).

**Figure 1.** Scheme of ER and water generation, wastewater and LHG utilization in PP of the EC.

The internal structure of PP 3.1...3.L depends on the profile of the OGE [34, 35]. In particular, for objects of the processing profile, a single PP module with a gas turbine unit (GTU) has the composition of equipment shown in Figure 2 (RU 2018 111 782).

In the PP carries out a combined generation of heat and electricity, cold and industrial water with the disposal of industrial combustible waste, and wastewater in a thermal-neutralizer (RU 2523906). There is also a solution for the use of RES (a hydrogen and oxygen generation unit: wind power generator 31, electrolyzer 32, hydrogen storage tanks 33 and oxygen 36), which makes it possible to replace part of the hydrocarbon fuel in the neutralizer with hydrogen. Mixing oxygen with industrial wastewaters provides an increase in the interface area and the rate of complete burnout of the wastewater.

The modular of PP shown in Figure 2 is integrated into the EC in the form of autonomous energy supply systems (RU 164323). It is possible to combine this PP (or individual elements of PP) with various technological objects [32, 34 and 35]:

- installations for transportation and storage of hydrocarbons (RU 118360);
- blocks of regeneration of absorbents of enterprises of extraction, preparation and processing of OGCF (RU 138474);
- power stabilization units for gas turbine drives of process blowers and CCGT (RU 149419).
1 – GTU – thermal engine; 2 – smoke gate; 3, 4 – exhaust heat boilers; 5 – steam extraction turbine; 6, 21 – electric power generators; 7 – condenser – heat exchanger; 8, 9, 11, 18 – pumps (8 – network circulation pump, 9, 11 – feed pumps, 18 – steam jet pump); 10 – condensed water de-aeration (de-carbonization) unit; 12, 27 – air conditioning condensers; 13 – neutralization tank for industrial waste water; 14, 22 – smoke funnels; 15 – gas pipe; 16 – smoke gate; 17, 23 – nozzles; 19 – condensed water cooler; 20 – filter; 24 – by-pass pipe junction; 25 – steam drive of compression refrigerator; 26 – compressor; 28 – thermal expansion valve; 29 – evaporator; 30 – steam flow regulator; 31 – wind power generator; 32 – electrolysis cell; 33 – hydrogen storage circuit; 34, 35 – fuel and hydrogen mixing vessel; 36 – oxygen storage circuit; 37 – industrial waste water and oxygen mixing vessel; I, II – fuel gas (hydrocarbon fuel); III – air; IV – industrial and utility wastes (effluents); V – condensed water; VI – unpurified condensed waste steam; VII, VIII, IX – flue gases; H2 – hydrogen; O2 – oxygen; X, XI – direct and reverse water flows of heat supply system; XII – overheated steam; XIII – reagent (sulfur oxides absorbent) solution; XIV – cooling agent; XV, XVI – heated and cooled coolant; XVII – water flow going to utility water pre-processing unit; * – PP module connection.

**Figure 2.** Scheme of PP for generating electric and heat energy, cold and water.

The structure of PP 3.L, in which the production of technological products is carried out, can be represented by ETS for the production of ER and carbon black (RU 2652237).

The connection of the technological block (Figure 3) of this PP with the power block shown in Figure 2 is carried out by the flow of flue gases (VIII) coming from the reactor to the waste heat boiler, and wastewaters (IV), which are disposed of in the neutralizer.

The feed (make-up) of the transporting agent (flow XV in Figure 3) is a part of the flue gases after the waste heat boiler in the power unit (the flow after the waste heat boiler 4 in Figure 2). The feed gas (stream II in Figure 3) is the LHG and / or flare gases of OGE.

Associated petroleum gas can be processed at the enterprises for the production and preparation of oil and gas-condensate in the PP with the production of carbon black and ER [32].

**3. Method for assessing the efficiency of PP**

To assess the efficiency of the PP as part of the EC of OGE, a system of combined indicators has been developed that covers the technological and economic activities of the OGE as an economic object and its characteristics as a consumer and generator of ER and water in interrelation with EESS and ecosystems of the region.
In accordance with this approach, the generalized multicriteria efficiency index (MEI) of the PP is represented by two equivalent groups of indicators: effectiveness (Es) and efficiency (Ey) [30–32].

The first group Es includes the following technical and economic criteria:
- $C_1$ – the value of sold products;
- $C_2$ – the cost of OGCF, other raw materials, catalysts and auxiliary materials;
- $C_3$ – costs of ER from EESS and water from external sources;
- $C_4, C_5$ – costs for equipment maintenance, repair and depreciation;
- $C_6$ – the payment to third-party enterprises for services for the treatment and disposal of waste and effluents.

The indicators of the second group Ey are presented in the form of vector functions, in which the particular energy, technological, economic indicators of efficiency $e_{ji}$ are ranked according to the method of hierarchy analysis [25]:

$$E_j = \sum_{i=1}^{k} b_i \bar{e}_{ji}, \quad (1)$$

where $b_i$ is rank coefficients (significance) of a particular indicator; $\bar{e}_{ji}$ is the normalized (dimensionless) value of the private indicator in the set of alternatives to the PP for the considered OGE.

The matrix of the coefficients of the rank of particular indicators for their various quantity in function (1) is given in Table 1.

The sign of the rank coefficient is determined by the physical meaning of a particular indicator: the indicator in function (1) has a negative or positive value.

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**Figure 3.** Scheme of PP technological block.
The six performance criteria $E_i$ of the $E_y$ group include the following components of function (1) $e_{ji}$ with the corresponding signs in front of the rank coefficient $b_i$ [31, 32 and 34]:

- $E_1$ – the use of OGF, materials and technological waste for the production of products:
  $+\bar{e}_{11}$ is the normalized (relative to the base variant) performance for the target products of the OGE;
  $+e_{12}$ is the utilization factor of OGF ($0 < e_{12} \leq 1$);
  $+e_{13}$ is the utilization factor of OGF and waste that were used to produce the by-products;
  $+\bar{e}_{14}$ is the normalized difference between the value of sold products and the cost of OGF, canalization and auxiliary materials;
  $+e_{15}$ is coefficient of rationalization of costs for fuel and ER from EESS;

- $E_2$ – the criterion of rationalization of material, energy and fuel balances:
  $+\bar{e}_{21}$ is the normalized specific (per unit of target product or OGF) consumption of fuel and ER;
  $+e_{22}$ is the coefficient of relative deviation (saving) of fuel and ER consumption;
  $-e_{23}$ is the factor of rationalization of energy technological balance;
  $-e_{24}$ is the factor of rationalization of water consumption balance;
  $-e_{25}$ is the factor of rationalization of balance of water disposal;
  $-\bar{e}_{26}$ is the normalized value of the technologically feasible potential for utilization of all types of ER, including RER;

- $E_3$ – the utilization of RER and fuel generated in the TS of OGE to generate the ER:
  $+e_{31}$ is energy efficiency coefficient equal to the ratio of the sum of useful additionally generated energy to the sum of the supplied energy from EESS, ETS, own sources of EC of OGE and PP;
  $+e_{32}$ is the efficiency coefficient for utilization of all types of ER;
  $+e_{33}$ is the efficiency coefficient of RER utilization for the generation of heat energy for own needs of the OGE;
  $+e_{34}$ is the exergy efficiency of OGE [29, 32] (without exergy of flows I and II in Figure 1);
  $+\bar{e}_{35}$ is the normalized value of systemic fuel savings resulting from installing own generating sources in the EC of OGE based on the PP;

- $E_4$ – normalized value of the productivity of the OGE for OGF processing ($E_4 = +\bar{e}_{11}$);

- $E_5$ – reliability of supply of ER and water, reliability of systems of waste disposal and wastewater:
  $+\bar{e}_{51}$ this the normalized value of the costs for alternative PP options for the creation of reserve electric and heat capacities, as well as additional costs of the EESS for servicing this reserve (in the case of maintaining connection with the EESS) and compensation costs resulting from changes in the balance of electric and thermal power of the system;
  $+\bar{e}_{52}$ is the normalized capital costs for reserve technological equipment, depending on technological, design factors, and operating time of the OGE;

- $E_6$ – the criterion environmental, industrial and general technical safety:
  $-e_{61}$ is the factor of rationalization of energy technological balance; $-\bar{e}_{61} = -e_{23}$;
  $-e_{62}$ is the factor of rationalization of water consumption balance; $-\bar{e}_{62} = -e_{24}$;
  $-e_{63}$ is the factor of rationalization of balance of water disposal; $-\bar{e}_{63} = -e_{25}$;
$+\bar{e}_{64}$ is the normalized capital costs in the technological equipment of waste, industrial effluent and emissions utilization enterprises, depending on technological, design factors, and the operating time of the OGE.

The multitudes $E_s$ and $E_y$ are equivalent and are determined for the corresponding period of operation of the OGE or for its entire life cycle.

The normalized MEI value in the corresponding time period is determined as the sum of the criteria of the $E_s$ and $E_y$ multitudes:

$$MEI(t) = 0.5 \sum_{p=1}^{6} a_p d_p m_p \bar{C}_p(t) + 0.5 \sum_{j=1}^{6} a_j f_j n_j \bar{E}_j(t), \quad (2)$$

where $a_p$ and $a_j$ is direction factors; $d_p$ and $f_j$ is balance coefficients; $m_p$ and $n_j$ is weight coefficients; $\bar{C}_p(t)$ and $\bar{E}(t)$ is the normalized criteria of effectiveness and efficiency (normalization was performed for the compared alternatives of the PP and the basic variants of EC of OGE).

Direction factor values:
- $a_p = +1$ for $\bar{C}_1$, $\bar{C}_2$, $\bar{C}_3$, $\bar{C}_4$, $\bar{C}_5$ and $\bar{C}_6$;
- $a_j = +1$ for $\bar{E}_1$, $\bar{E}_2$, $\bar{E}_4$ and $\bar{E}_5$; $a_j = -1$ for $\bar{E}_3$ and $\bar{E}_6$.

The balance coefficients $d_p$ and $f_j$ are 1/6 if the criterion is the only one in the multitudes $E_s$ or $E_y$, and multiplied by the corresponding number for multiple calculations in each multitude:
- $d_p = 1/6$ for $\bar{C}_1$; $d_p = 5/6$ for $\bar{C}_2$, $\bar{C}_3$, $\bar{C}_4$, $\bar{C}_5$ and $\bar{C}_6$;
- $f_j = 1/6$ for $\bar{E}_4$; $f_j = 3/6$ for $\bar{E}_1$, $\bar{E}_2$ and $\bar{E}_4$; $f_j = 2/6$ for $\bar{E}_3$ and $\bar{E}_6$.

Weighting factors allow to determine the significance of each criterion in the multitudes $E_s$ and $E_y$:

$$m_p = \frac{\bar{C}_p}{\sum_{p=1}^{6} \bar{C}_p \sum_{j=1}^{6} \bar{E}_j}; \quad n_j = \frac{\bar{E}_j}{\sum_{p=1}^{6} \bar{C}_p \sum_{j=1}^{6} \bar{E}_j}; \quad (3)$$

The visualization of the relations of these multitudes is shown in Figure 4 in the form of a two-dimensional phase space of the MEI (in relative units without a time coordinate $t$), divided into quadrants.

**Figure 4.** Phase space of efficiency $E_y$ and effectiveness $E_s$.  

[Diagram of Figure 4 showing quadrants I, II, III, and IV with points A, B, C, D, and labels for MEI and Ey-Es axes.]
Each figurative point on the diagonal H corresponds to an object with zero MEI. Objects whose Es and Ey indices intersect in quadrants I, II, and IV above the H diagonal are characterized by positive MEI. The projection of a point characterizing a specific object onto the MEI coordinate is carried out by parallel translation of the diagonal H until it intersects with this point. For example, for point A (Ey = 0.33, Es = 0.78), the projection is point A′ (MEI = 0.553).

We carried out calculations to determine the MEI for a number of OGEs of the processing profile, preparation and transportation of oil and gas condensate using the developed information and analytical system [36] and methods of object-oriented design [37, 38]. The complete technological and energy characteristics of the OGEs explored are given in [32].

As a result, the studied OGEs are conventionally grouped in two areas of efficiency with fuzzy boundaries: S1 is the subjects for preparation and transportation of OGCF; S2 is the gas processing plants and their individual units of TS.

In the S2 area, point A characterizes a plant for the production of carbon black in the basic version, and point B - a combined continuous-action plant with a PP (Figures 2 and 3; RU 2652237). Intermediate points show the change in the Es and Ey indicators of a given object over time. At the initial stage (1.0 – 1.5 years), the effectiveness Es decreases somewhat (due to additional costs in the PP and the technological block of continuous operation) with an increase in the efficiency Ey. The planned indicators – point B (Ey = 0.59, Es = 0.864, MEI = 0.727) are reached in less than four years.

4. Conclusion
A concept for the synthesis of PP for the generation of electrical and thermal energy, cold and water has been developed on the basis of their integration with technological installations and systems for the utilization of effluents, combustible waste and low-pressure gases of OGE. Shown are examples of the implementation of the concept of synthesis of modular PP, in which the production of technological and energy products, wastewater disposal and water production are carried out. A method is proposed for assessing the effectiveness of PP based on the developed multi-criteria index of efficiency, which includes equivalent groups of indicators of technological, energy, economic and environmental effectiveness and efficiency. The results of the analysis of the efficiency of the polygeneration plant as part of the production of carbon black are given, which showed the feasibility of inter-production integration of technological and power systems.

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